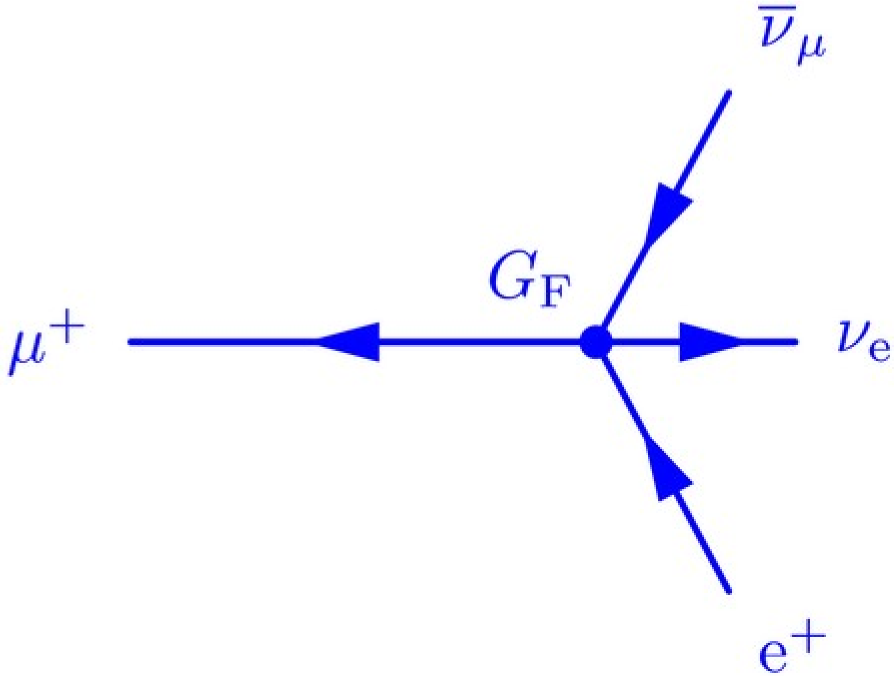
The MuLan Experiment
Measuring the muon lifetime to 1ppm

Kevin Lynch
MuLan Collaboration
York College, CUNY



Berkeley, Boston, Illinois,
James Madison, Kentucky, KVI, PSI

The MuLan Experiment

Measuring the muon lifetime to 1ppm

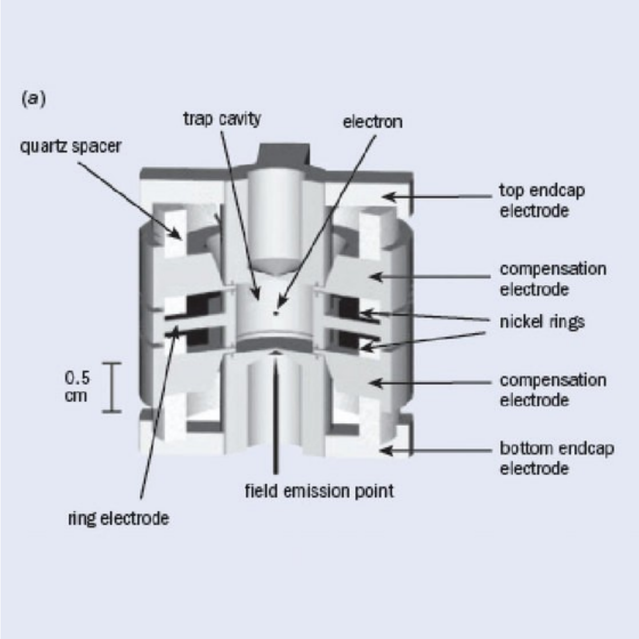
Kevin Lynch
MuLan Collaboration
York College, CUNY

Outline:
- Motivate the measurement
- Describe the experiment
- Results

Berkeley, Boston, Illinois,
James Madison, Kentucky, KVI, PSI

YORK College
THE CITY UNIVERSITY OF NEW YORK

Precision electroweak predictions rest on three input parameters



Fine Structure Constant

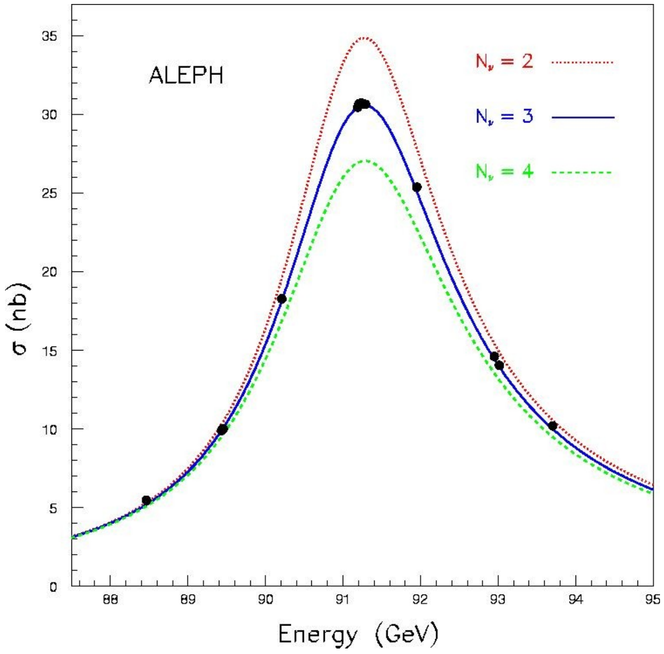
$$\frac{\delta\alpha_{\rm em}}{\alpha_{\rm em}} \approx 0.32\,\mathrm{ppb}$$

Gabrielse *et al* 2008

Mass of the neutral weak boson

$$\frac{\delta M_{Z^0}}{M_{Z^0}} \approx 23\,\mathrm{ppm}$$

LEP EWWG 2005



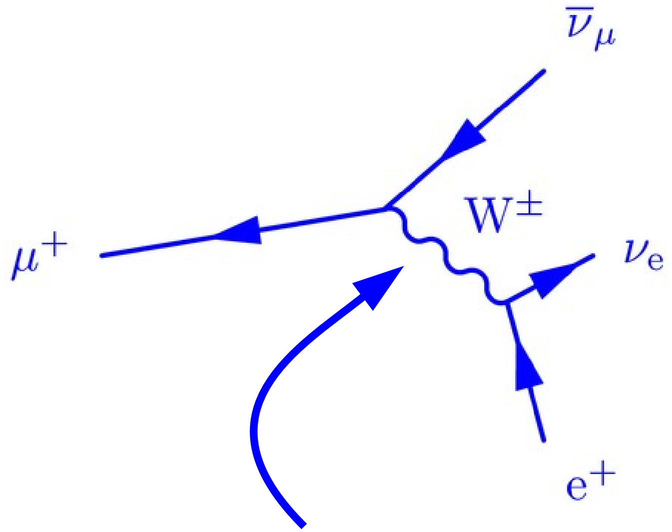
Fermi Constant

$$\frac{\delta G_{\rm F}}{G_{\rm F}} \approx 9\,\mathrm{ppm}$$

Giovanetti *et al* 1984

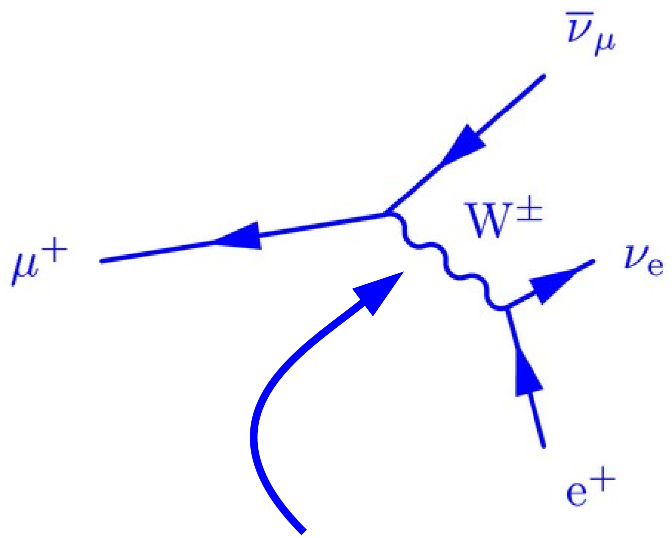
Muon decay gives us unique access to the electroweak scale

Muon decay gives us unique access to the electroweak scale



The muon *only* decays via the weak interaction, which gives it a very long lifetime.

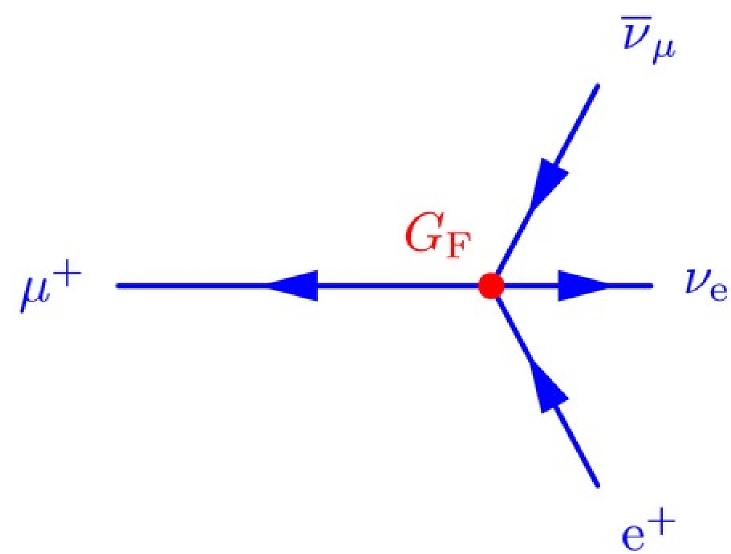
Muon decay gives us unique access to the electroweak scale



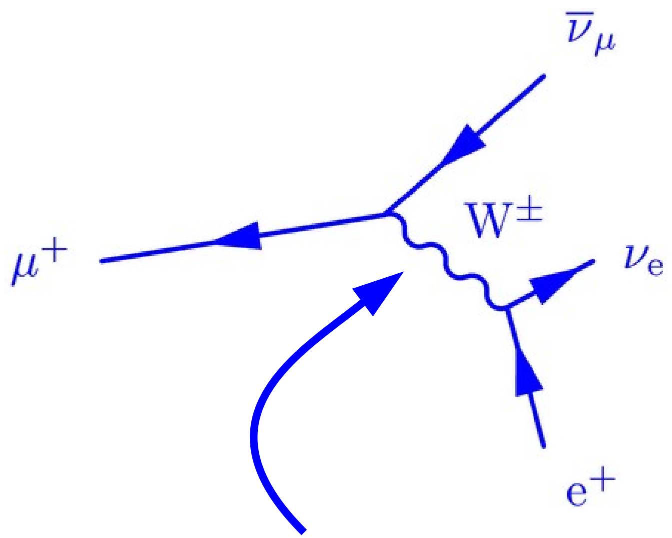
The muon *only* decays via the weak interaction, which gives it a very long lifetime.

The V-A theory factorizes into a pure weak contribution

$$\frac{1}{\tau_{\mu^+}} = \frac{G_F{}^2 m_\mu^5}{192\pi^3}$$



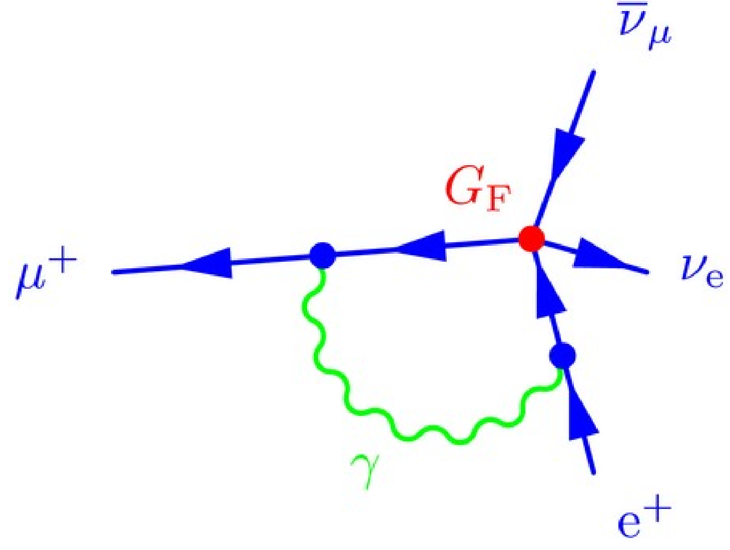
Muon decay gives us unique access to the electroweak scale



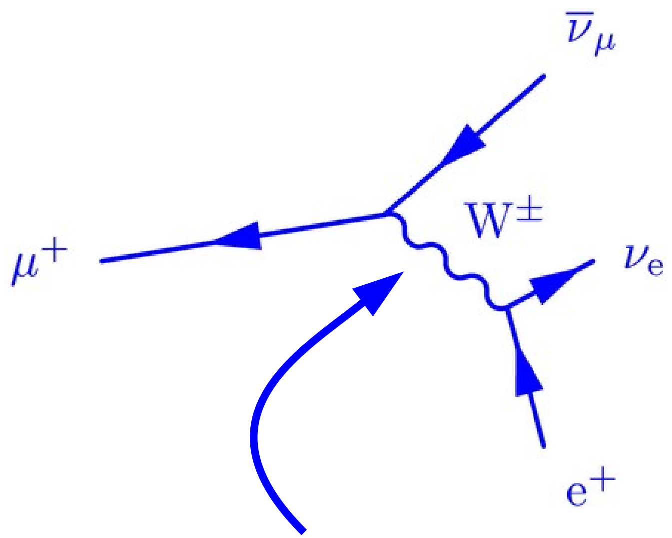
The muon *only* decays via the weak interaction, which gives it a very long lifetime.

The V-A theory factorizes into a pure weak contribution, and non-weak corrections, essentially uncontaminated by hadronic uncertainties.

$$\frac{1}{\tau_{\mu^+}} = \frac{{G_\mathrm{F}}^2 m_\mu^5}{192\pi^3}(1+q)$$



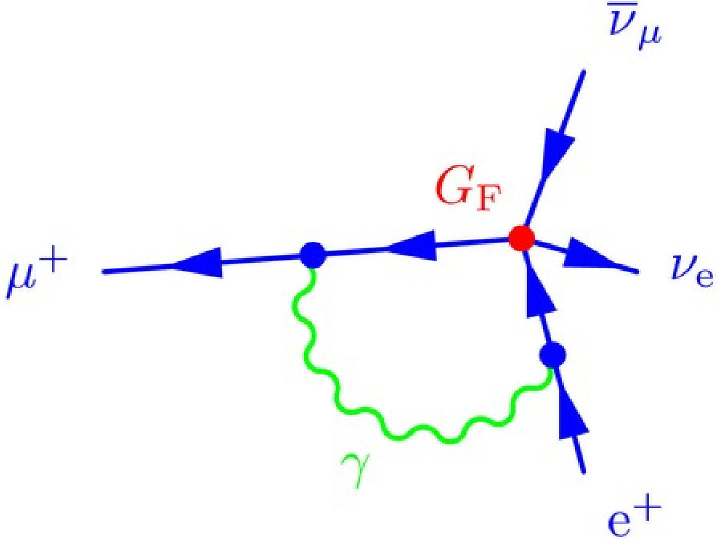
Muon decay gives us unique access to the electroweak scale



The muon *only* decays via the weak interaction, which gives it a very long lifetime.

The V-A theory factorizes into a pure weak contribution, and non-weak corrections, essentially uncontaminated by hadronic uncertainties.

$$\frac{1}{\tau_{\mu^+}} = \frac{{G_F}^2 m_\mu^5}{192\pi^3}(1+q)$$



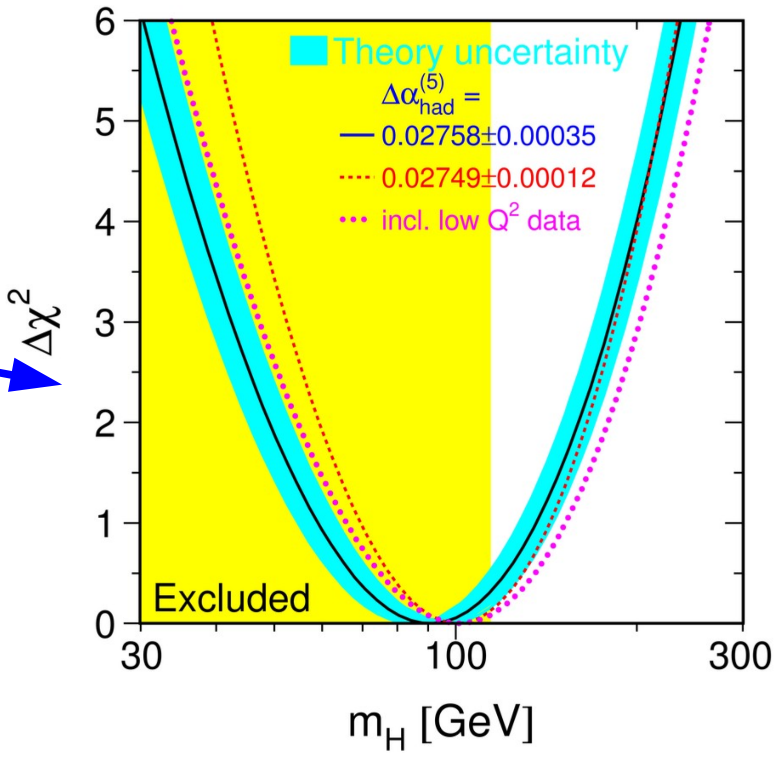
All relevant weak interaction physics is confined to one easily measured parameter with a clean theoretical interpretation.

The Fermi constant is an implicit input to all precision electroweak studies

$$\frac{G_{\mathrm{F}}}{\sqrt{2}} = \frac{g^2}{8M_{\mathrm{W}}^2}\left(1 + \Delta r(m_{\mathrm{t}}, m_{\mathrm{H}}, \ldots)\right)$$

Contains all weak interaction loop corrections.

Example: the “blue band” Higgs limit plot.



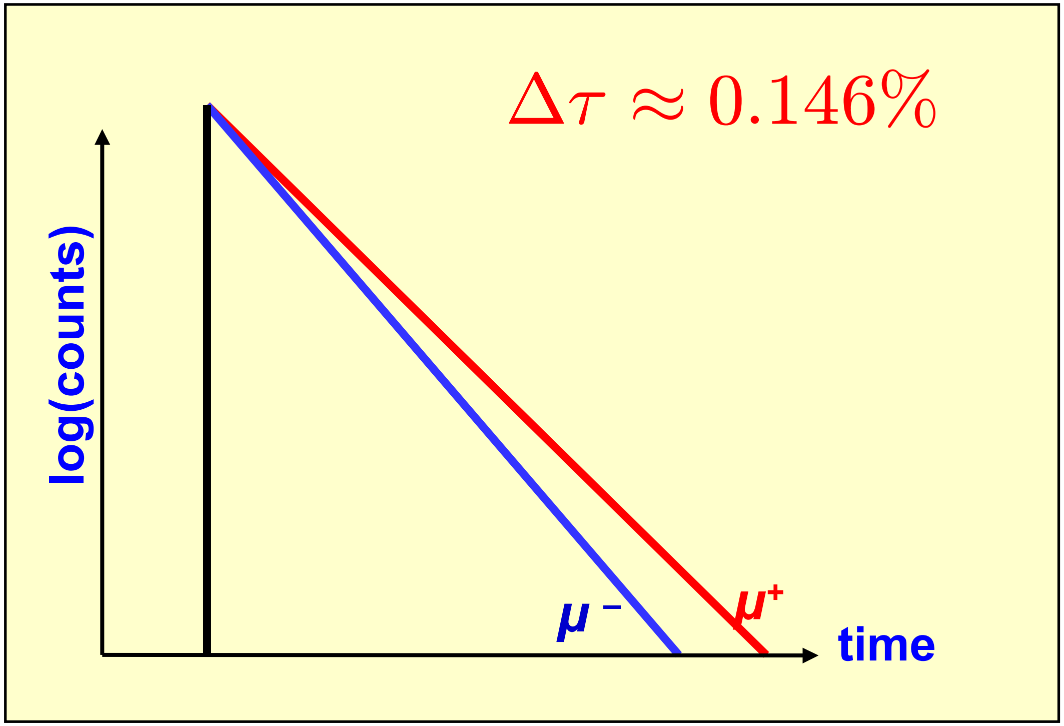
Plot borrowed from LEP Electroweak Working Group publications

Precision lifetime difference measurements yield information on nucleon weak structure

For example, the singlet capture rate on the proton gives direct access to the pseudoscalar nucleon coupling

$$\Lambda_S = \Lambda_{\mu^-} - \Lambda_{\mu^+} = \frac{1}{\tau_{\mu^-}} - \frac{1}{\tau_{\mu^+}}$$

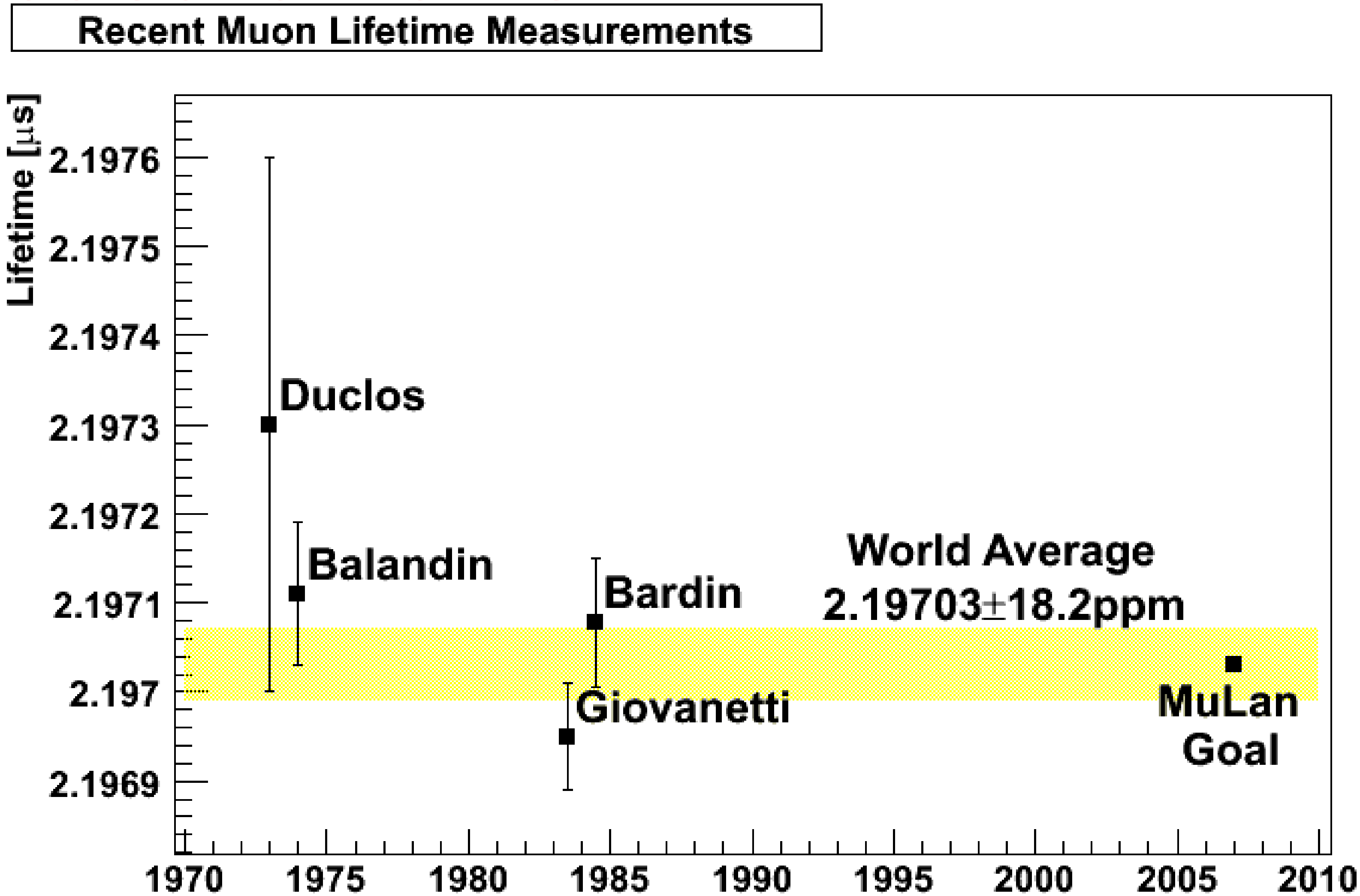
$$\frac{\delta \Lambda_S}{\Lambda_S} = 0.18 \frac{\delta g_P}{g_P}$$



The more accurately we measure the muon lifetimes, the more precisely we can extract derived quantities

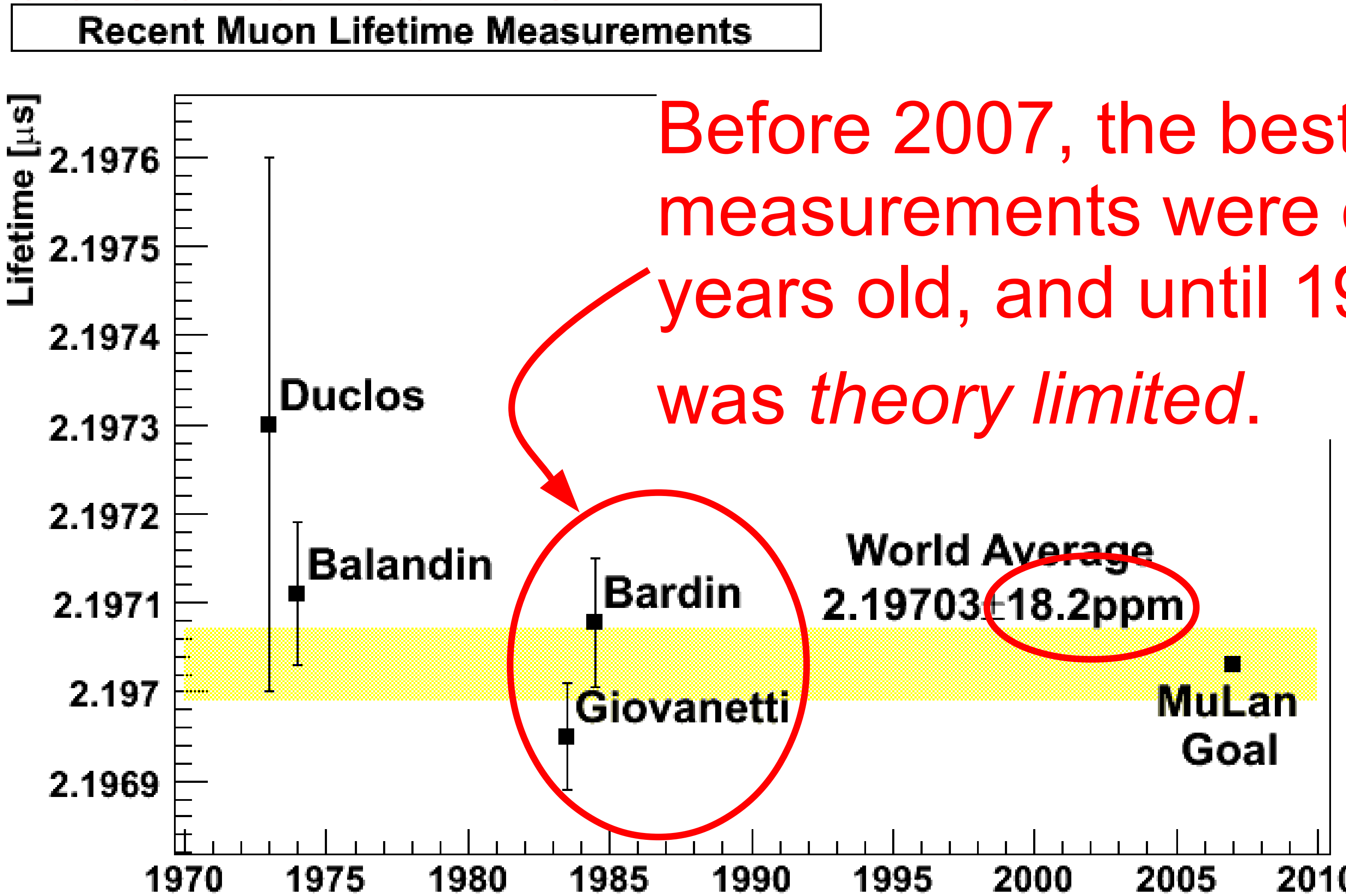
See MuCap talk by Brendan Kiburg immediately following

A brief history of muons lifetime measurements



G. Bardin et al., Phys. Lett. B 137, 135 (1984)
K. Giovanetti et al., Phys. Rev. D 29, 343 (1984)

A brief history of muons lifetime measurements



Before 2007, the best measurements were over 20 years old, and until 1999 G_F was *theory limited*.

G. Bardin et al., Phys. Lett. B 137, 135 (1984)
K. Giovanetti et al., Phys. Rev. D 29, 343 (1984)

Theory limitations were lifted in 1999

$$\frac{\delta G_\mathrm{F}}{G_\mathrm{F}} = \frac{1}{2}\sqrt{\left(\frac{\delta\tau_\mu}{\tau_\mu}\right)^2 + \left(5\frac{\delta m_\mu}{m_\mu}\right)^2 + \left(\frac{\delta\mathrm{theory}}{\mathrm{theory}}\right)^2}$$

Mid 90s: 17 ppm 18 ppm 90 ppb 30 ppm

Theory limitations were lifted in 1999

$$\frac{\delta G_{\mathrm{F}}}{G_{\mathrm{F}}} = \frac{1}{2}\sqrt{\left(\frac{\delta\tau_\mu}{\tau_\mu}\right)^2 + \qquad\qquad + \left(\frac{\delta\mathrm{theory}}{\mathrm{theory}}\right)^2}$$

Mid 90s: 17 ppm 18 ppm 30 ppm

Theory limitations were lifted in 1999

$$\frac{\delta G_\mathrm{F}}{G_\mathrm{F}} = \frac{1}{2}\sqrt{\left(\frac{\delta\tau_\mu}{\tau_\mu}\right)^2 + \qquad\qquad + \left(\frac{\delta\mathrm{theory}}{\mathrm{theory}}\right)^2}$$

1999: 9 ppm 18 ppm < 0.3 ppm

van Ritbergen and Stuart:
2-loop QED corrections
(massless electrons)

T. van Ritbergen and R. G. Stuart, Nucl. Phys. B564, 343 (2000)
A. Pak and A. Czarnecki, Phys. Rev. Lett. 100, 241807 (2008)

Theory limitations were lifted in 1999

$$\frac{\delta G_\mathrm{F}}{G_\mathrm{F}} = \frac{1}{2}\sqrt{\left(\frac{\delta\tau_\mu}{\tau_\mu}\right)^2 + \qquad\qquad + \left(\frac{\delta\mathrm{theory}}{\mathrm{theory}}\right)^2}$$

1999: 9 ppm 18 ppm < 0.3 ppm

Lifetime error limits the Fermi constant extraction

van Ritbergen and Stuart: 2-loop QED corrections (massless electrons)

T. van Ritbergen and R. G. Stuart, Nucl. Phys. B564, 343 (2000)
A. Pak and A. Czarnecki, Phys. Rev. Lett. 100, 241807 (2008)

Theory limitations were lifted in 1999

$$\frac{\delta G_{\mathrm{F}}}{G_{\mathrm{F}}} = \frac{1}{2}\sqrt{\left(\frac{\delta\tau_\mu}{\tau_\mu}\right)^2 + \qquad + \left(\frac{\delta\mathrm{theory}}{\mathrm{theory}}\right)^2}$$

Today: 0.5 ppm 1 ppm < 0.3 ppm

Lifetime error limits the Fermi constant extraction

How do you measure the muon lifetime?

How do you measure the muon lifetime?

$$\tau_\mu = 2.197\,\mu\mathrm{s}$$

How do you measure the muon lifetime?

One-at-a-time

$$\tau_\mu = 2.197\,\mu s$$

How do you measure the muon lifetime?

One-at-a-time

$$\tau_\mu = 2.197\,\mu\mathrm{s}$$

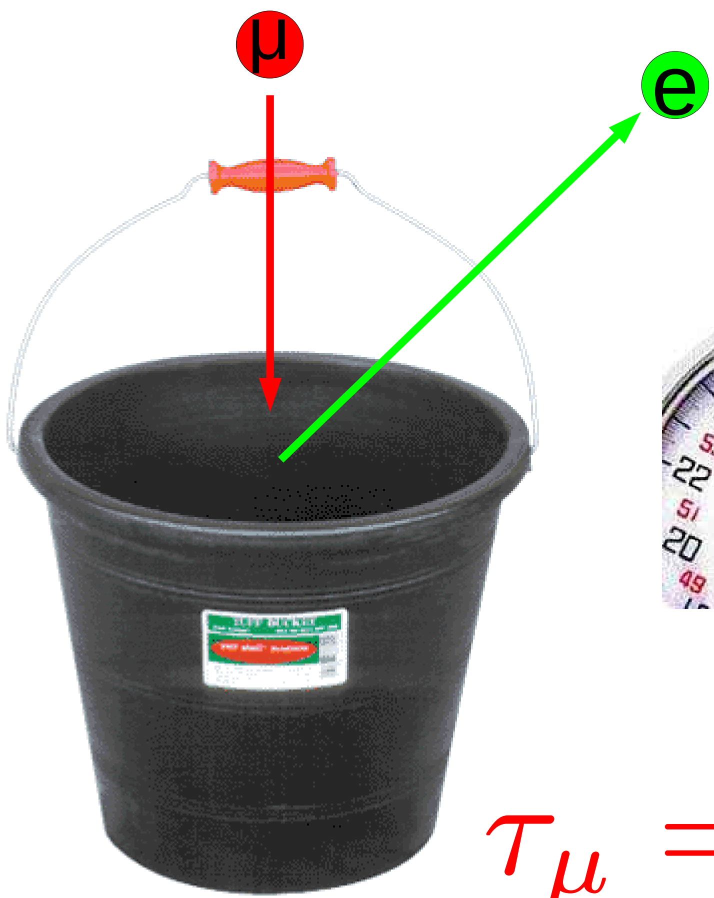
How do you measure the muon lifetime?

One-at-a-time

$$\tau_\mu = 2.197\,\mu\mathrm{s}$$

How do you measure the muon lifetime?

One-at-a-time

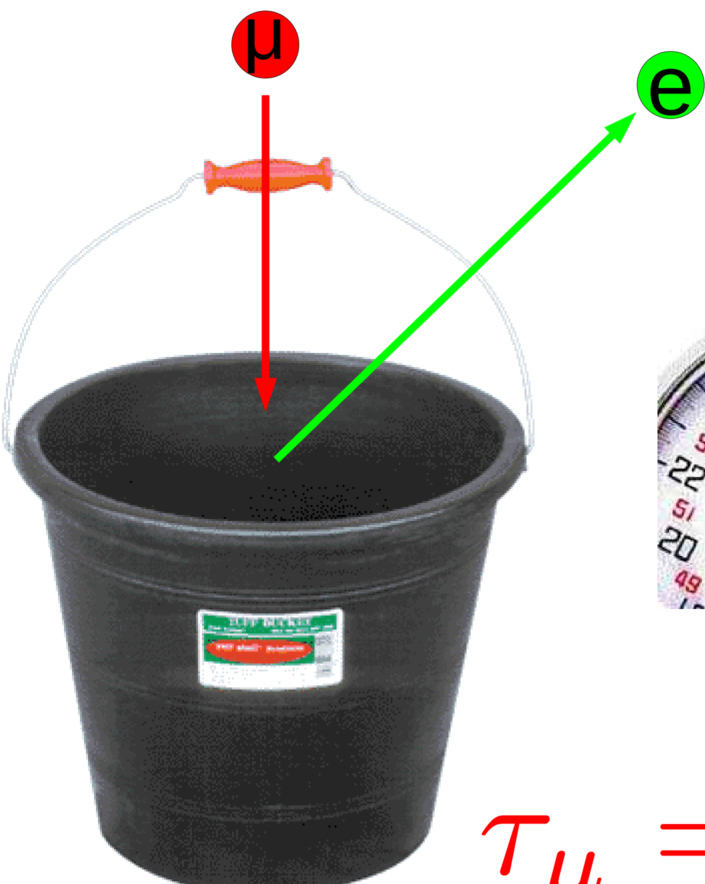


$$\tau_\mu = 2.197\,\mu\mathrm{s}$$

How do you measure the muon lifetime?

One-at-a-time

Many-at-once

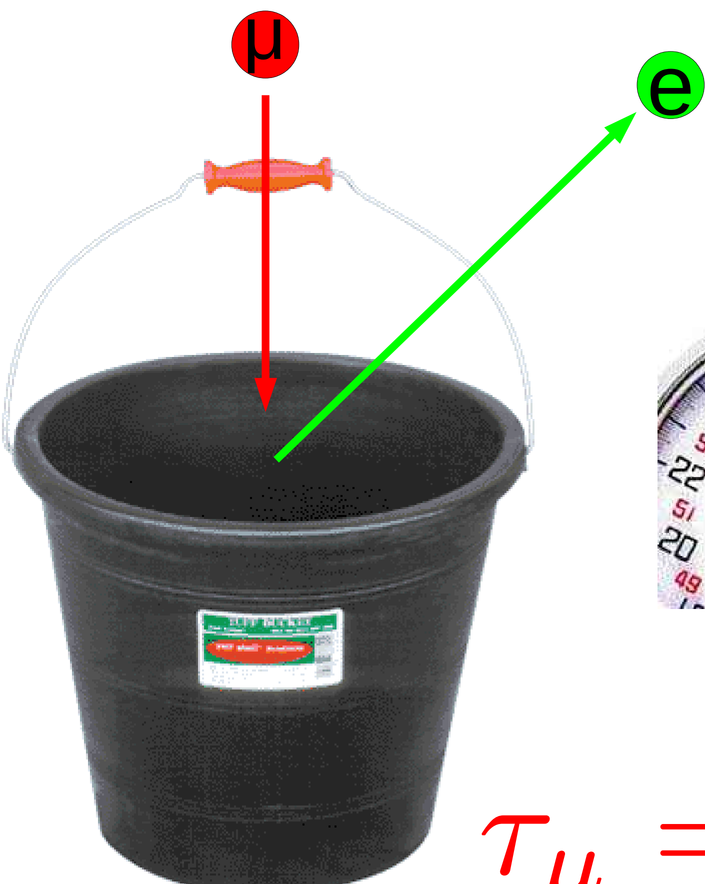


$$\tau_\mu = 2.197\,\mu\mathrm{s}$$

How do you measure the muon lifetime?

One-at-a-time

Many-at-once

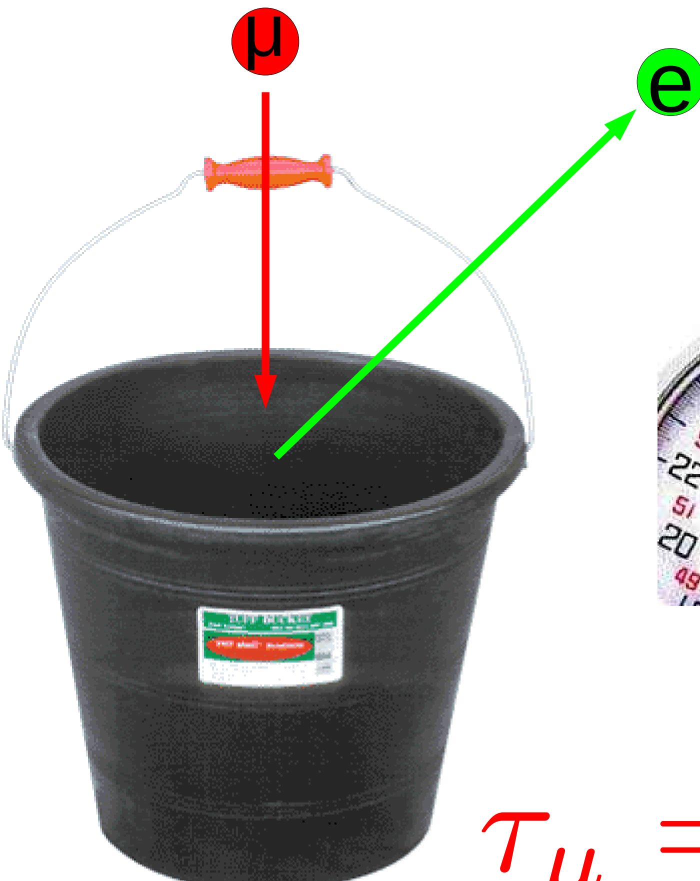


$$\tau_\mu = 2.197\,\mu\mathrm{s}$$

How do you measure the muon lifetime?

One-at-a-time

Many-at-once

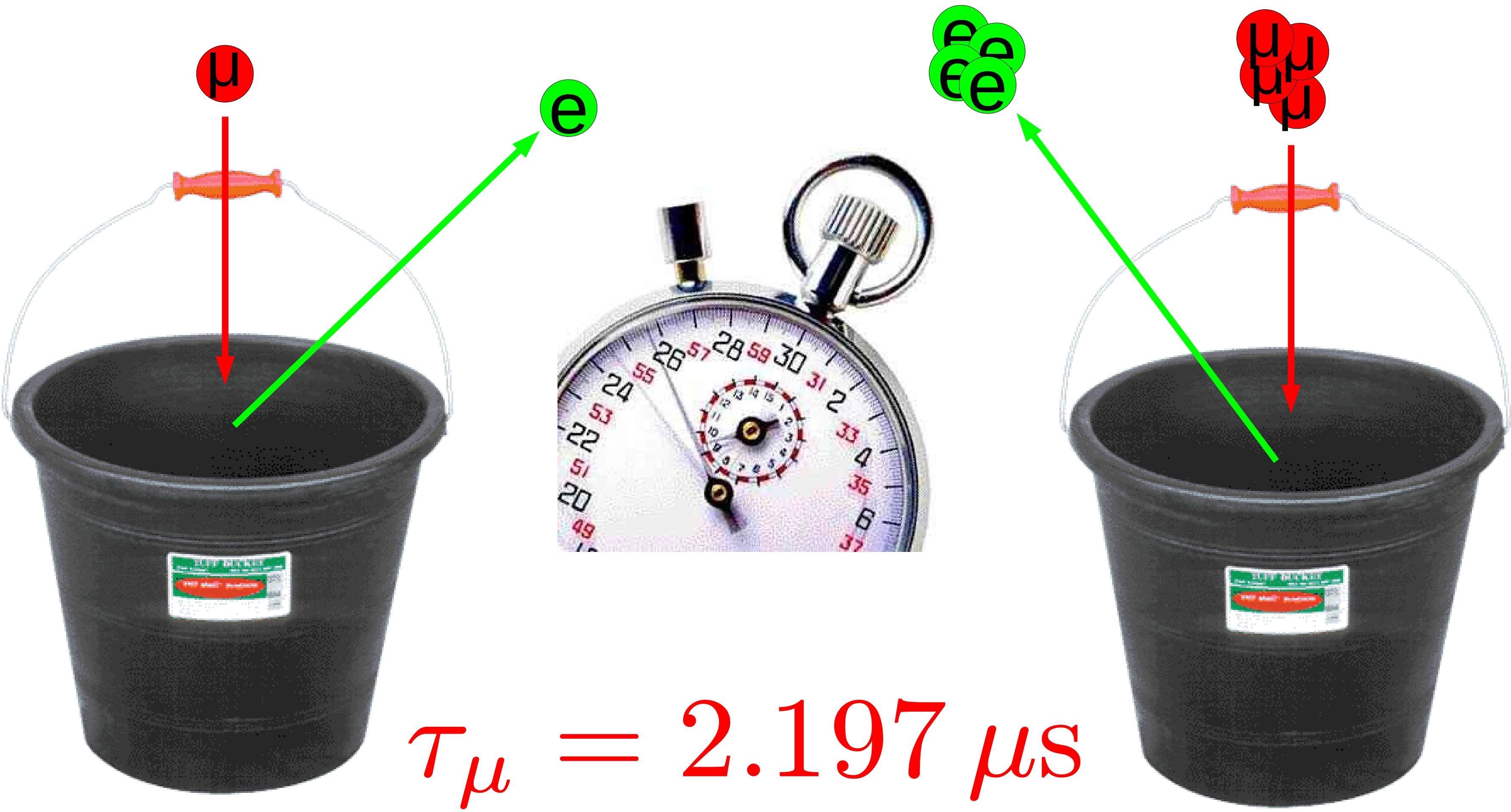


$$\tau_\mu = 2.197\,\mu s$$

How do you measure the muon lifetime?

One-at-a-time

Many-at-once



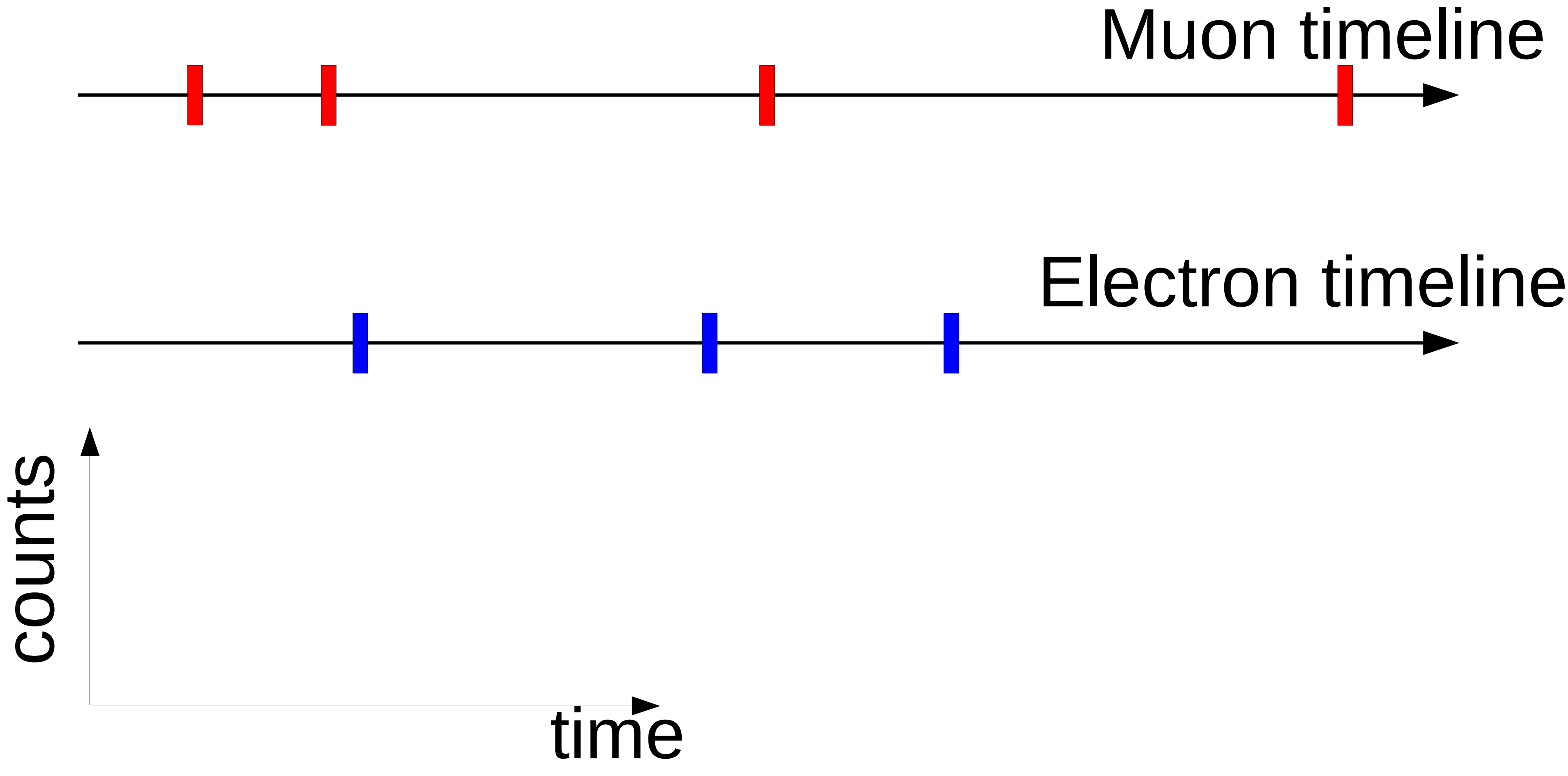
$$\tau_\mu = 2.197\,\mu\mathrm{s}$$

One-at-a-time

Can't really do one-at-a-time, the next best thing is a low rate, DC beam.

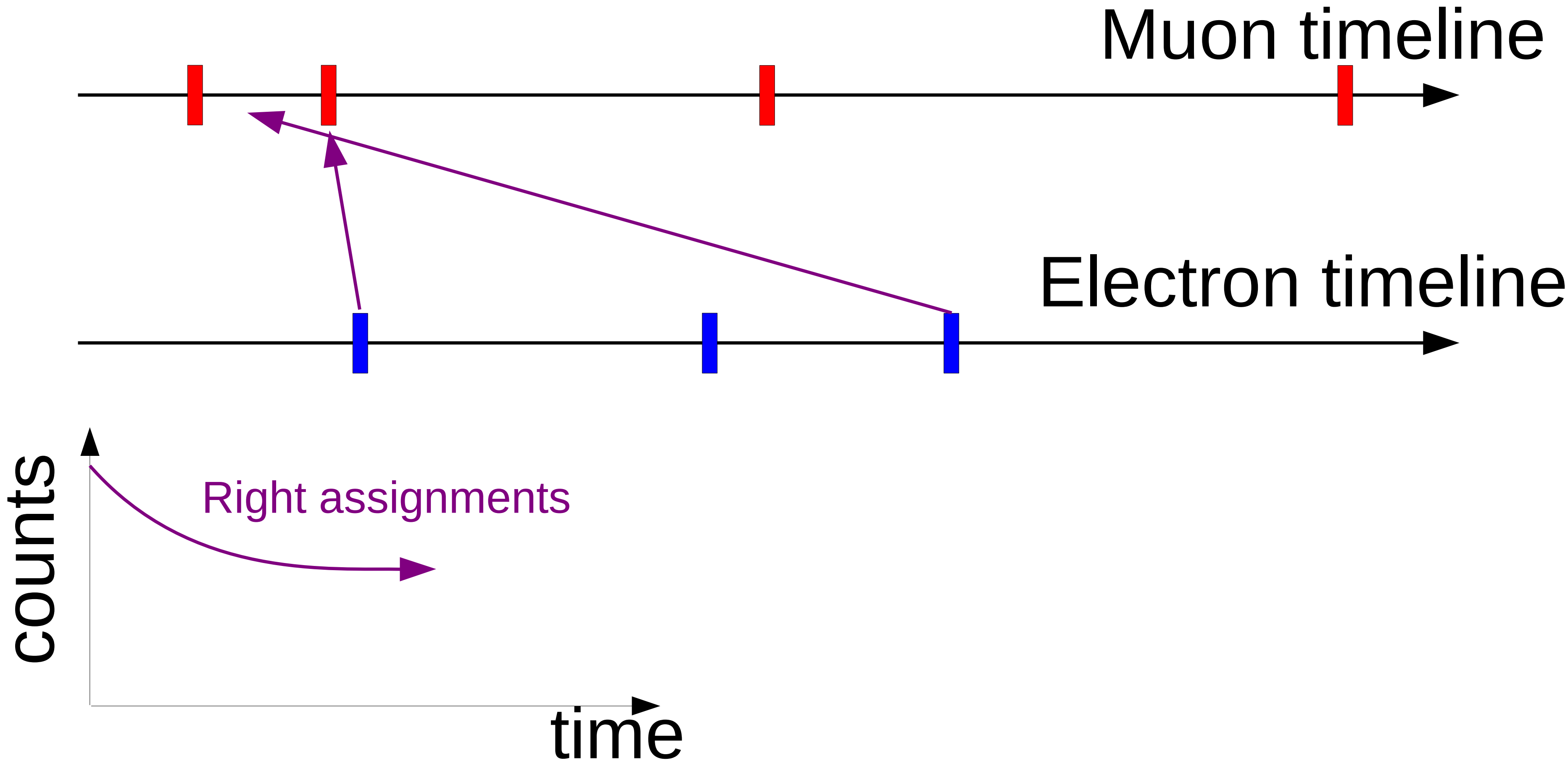
One-at-a-time

Can't really do one-at-a-time, the next best thing is a low rate, DC beam.



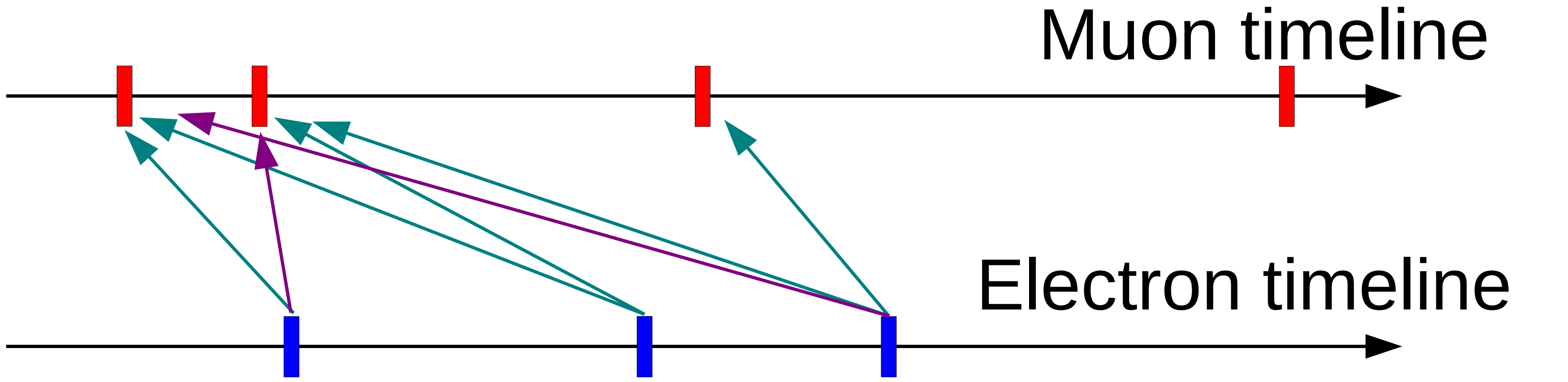
One-at-a-time

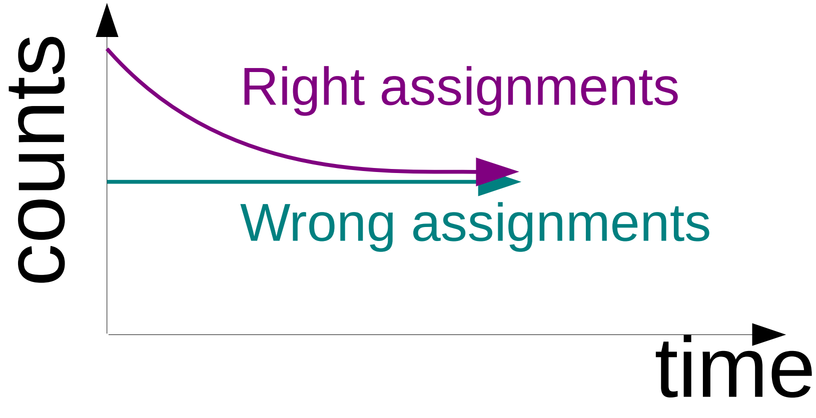
Can't really do one-at-a-time, the next best thing is a low rate, DC beam.



One-at-a-time

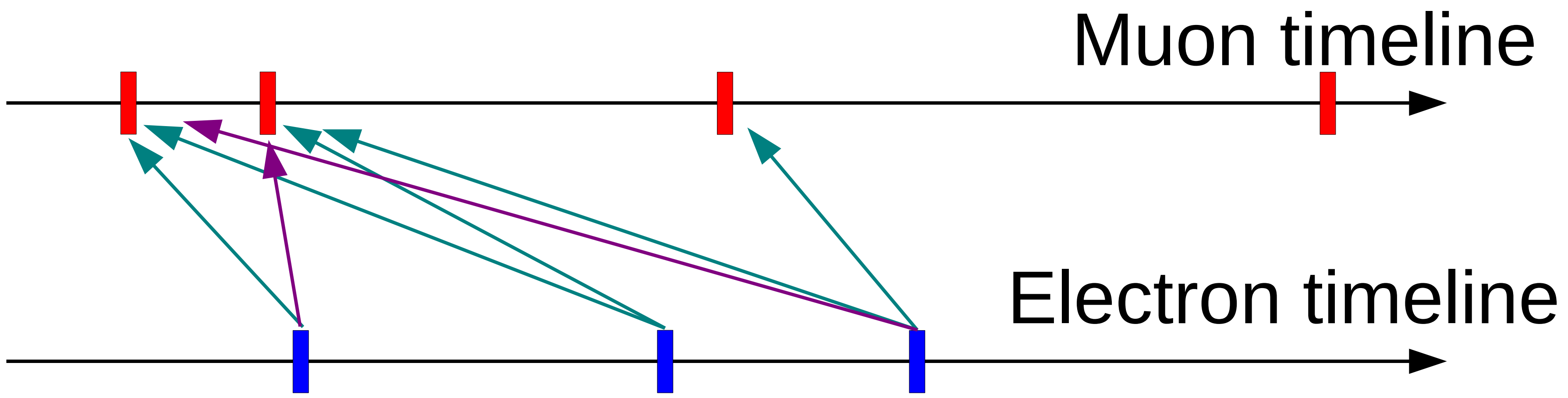
Can't really do one-at-a-time, the next best thing is a low rate, DC beam.

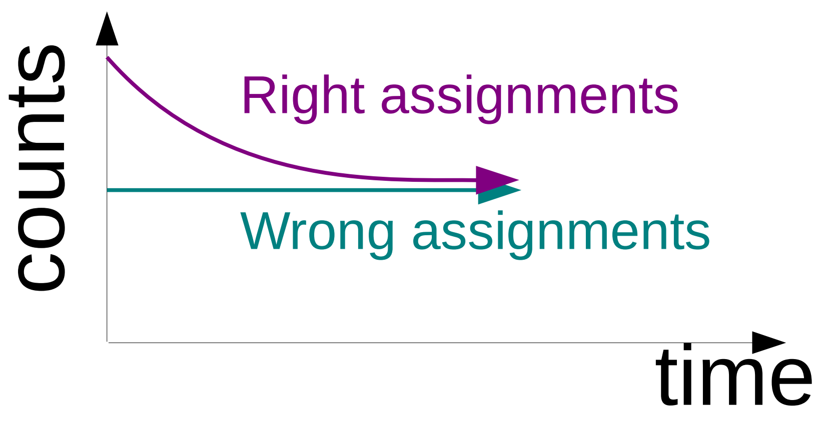




One-at-a-time

Can't really do one-at-a-time, the next best thing is a low rate, DC beam.





$$\frac{S}{B} \propto \frac{N}{N^2} = \frac{1}{N}$$

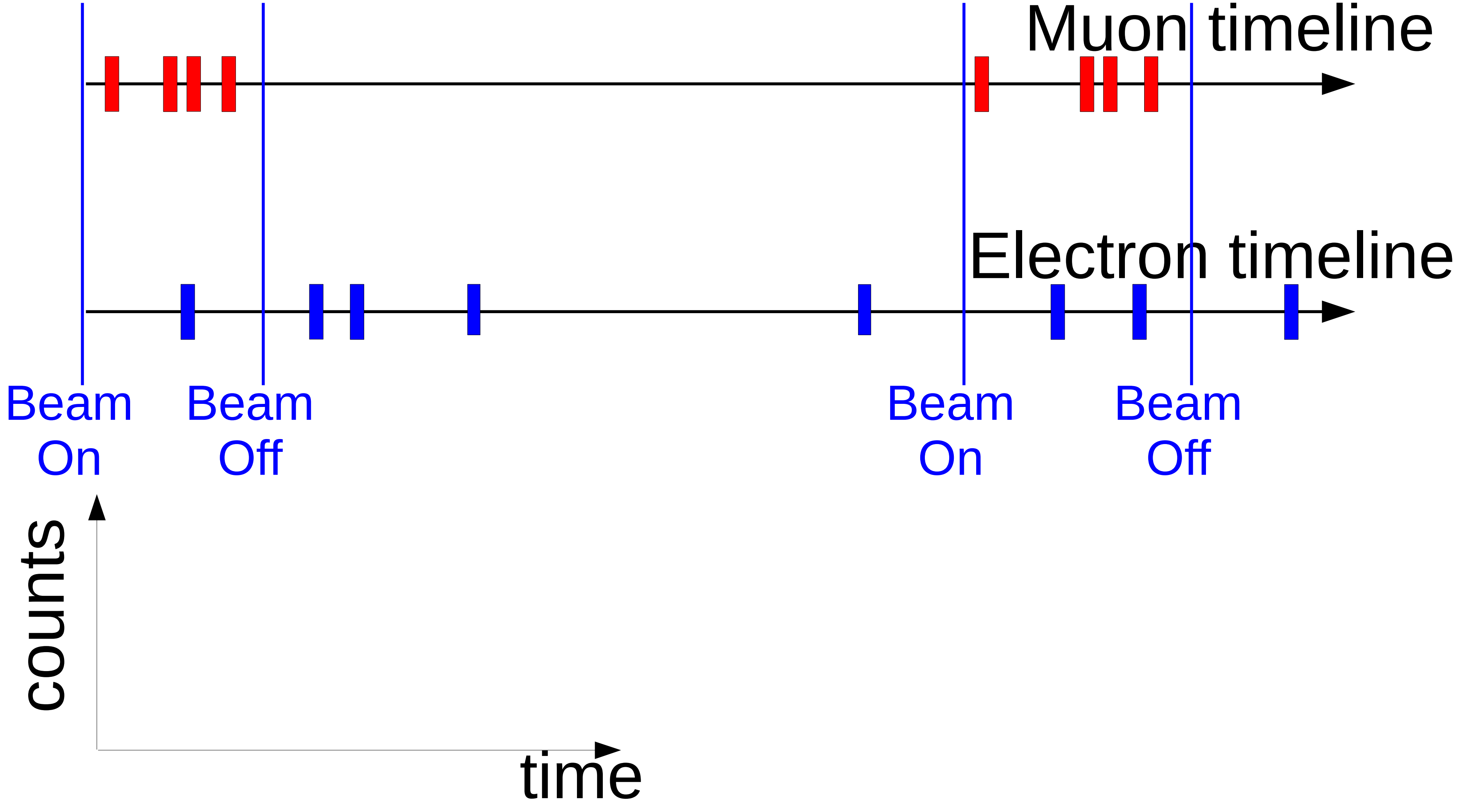
$$30\,\mathrm{kHz} \rightarrow 385\,\mathrm{d}\ \mathrm{for}\ 10^{12}\mu^+$$

Many-at-once

Need time structured (AC) beam, not a continuous (DC) beam

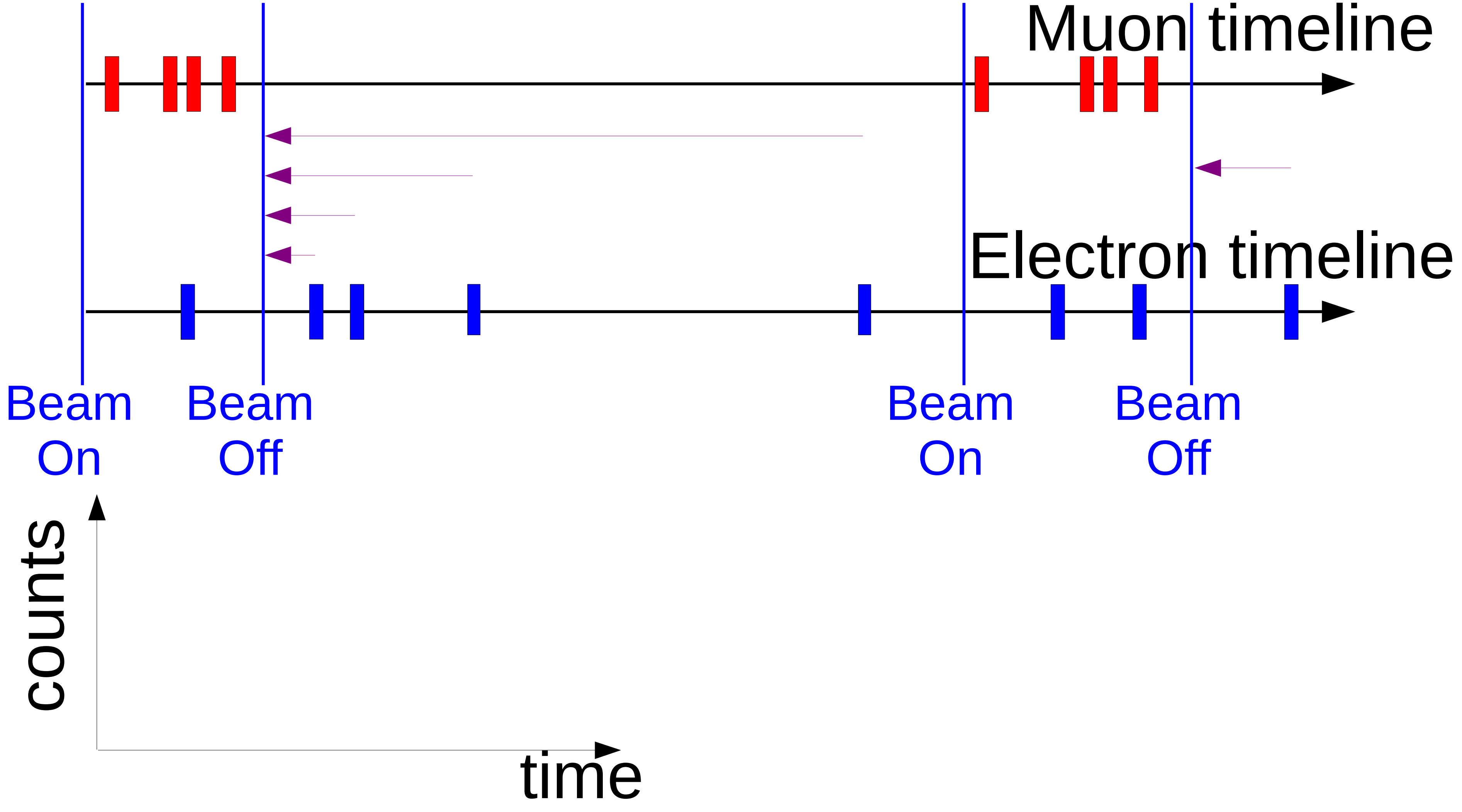
Many-at-once

Need time structured (AC) beam, not a continuous (DC) beam



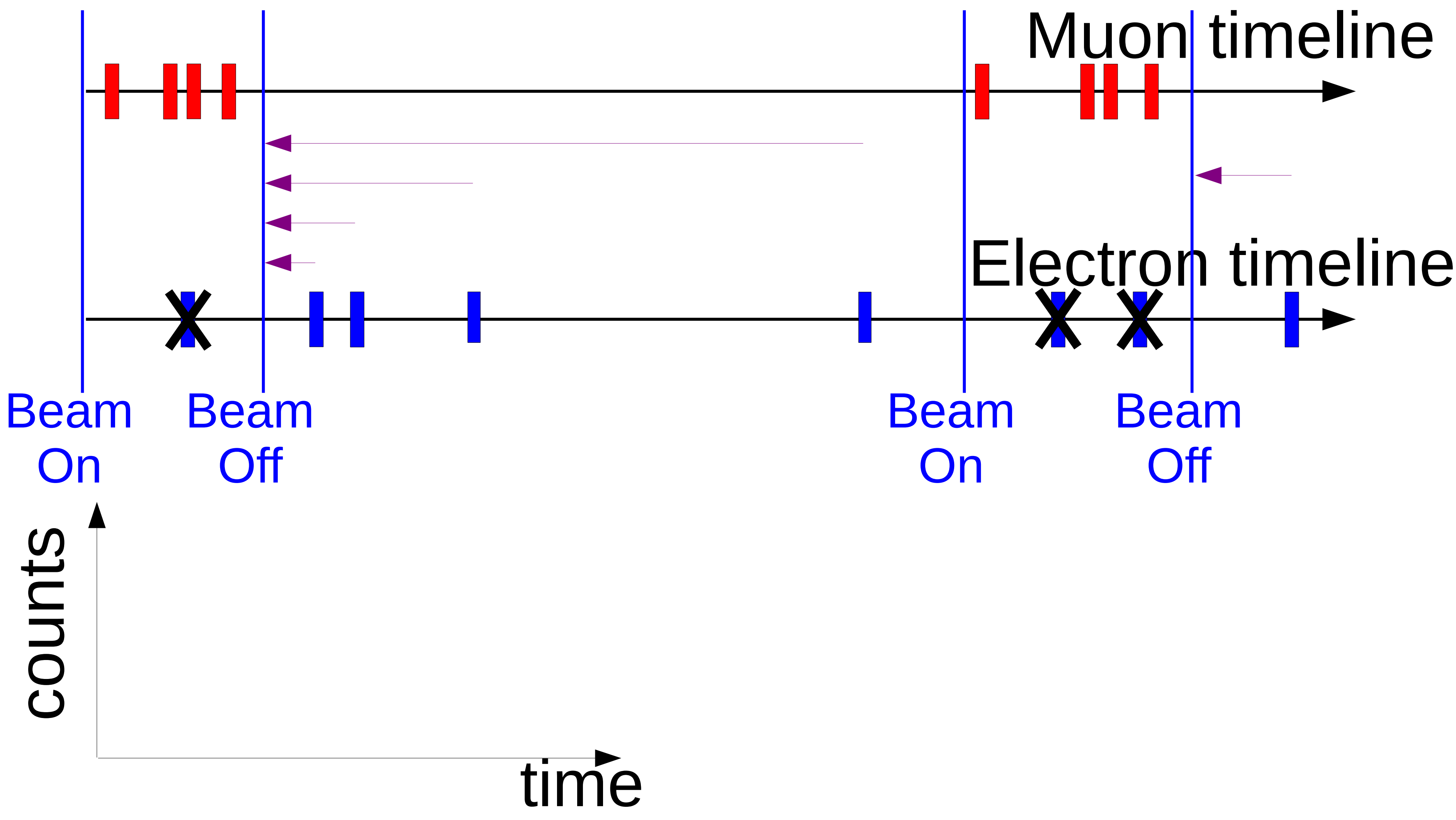
Many-at-once

Need time structured (AC) beam, not a continuous (DC) beam



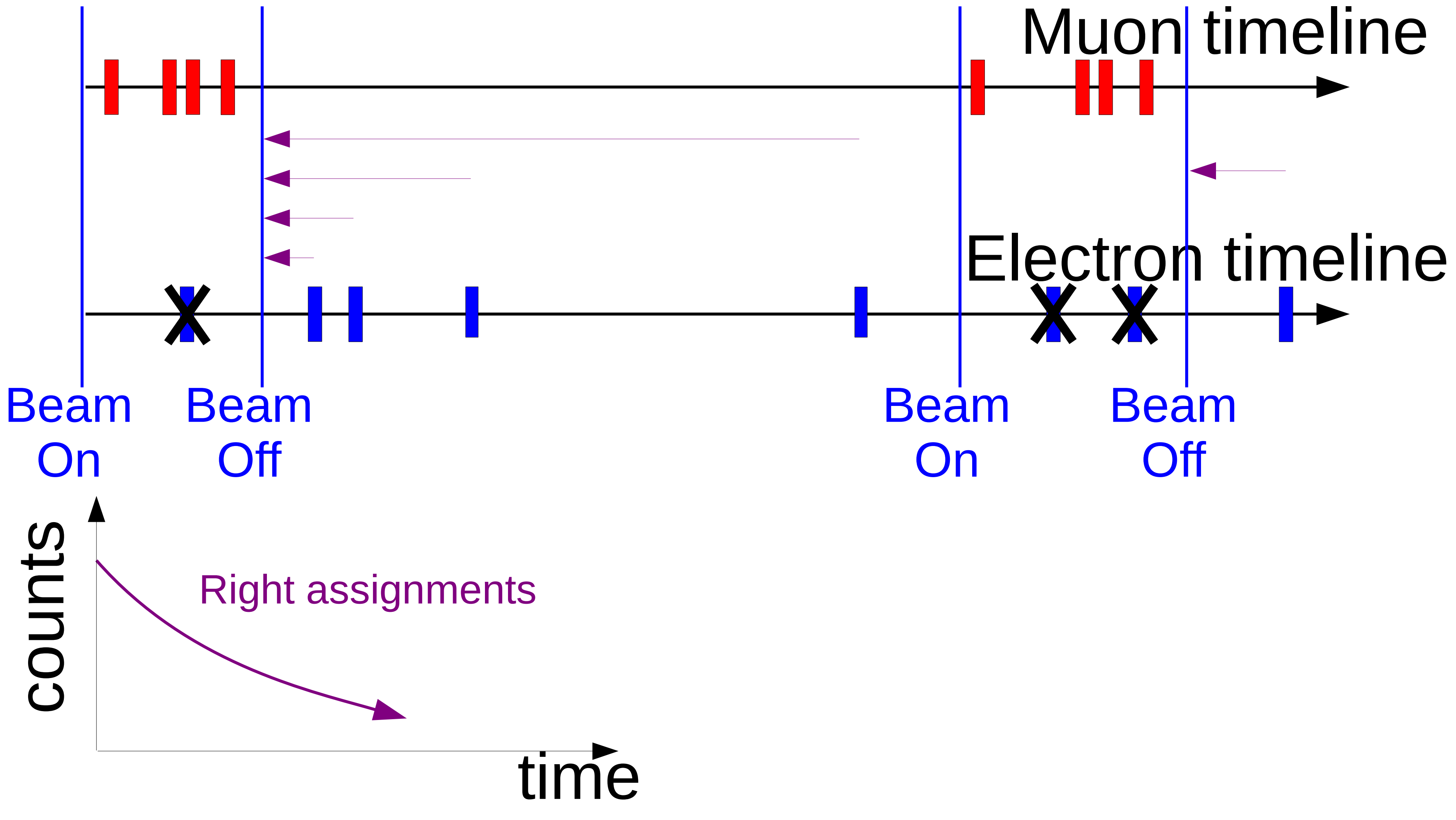
Many-at-once

Need time structured (AC) beam, not a continuous (DC) beam



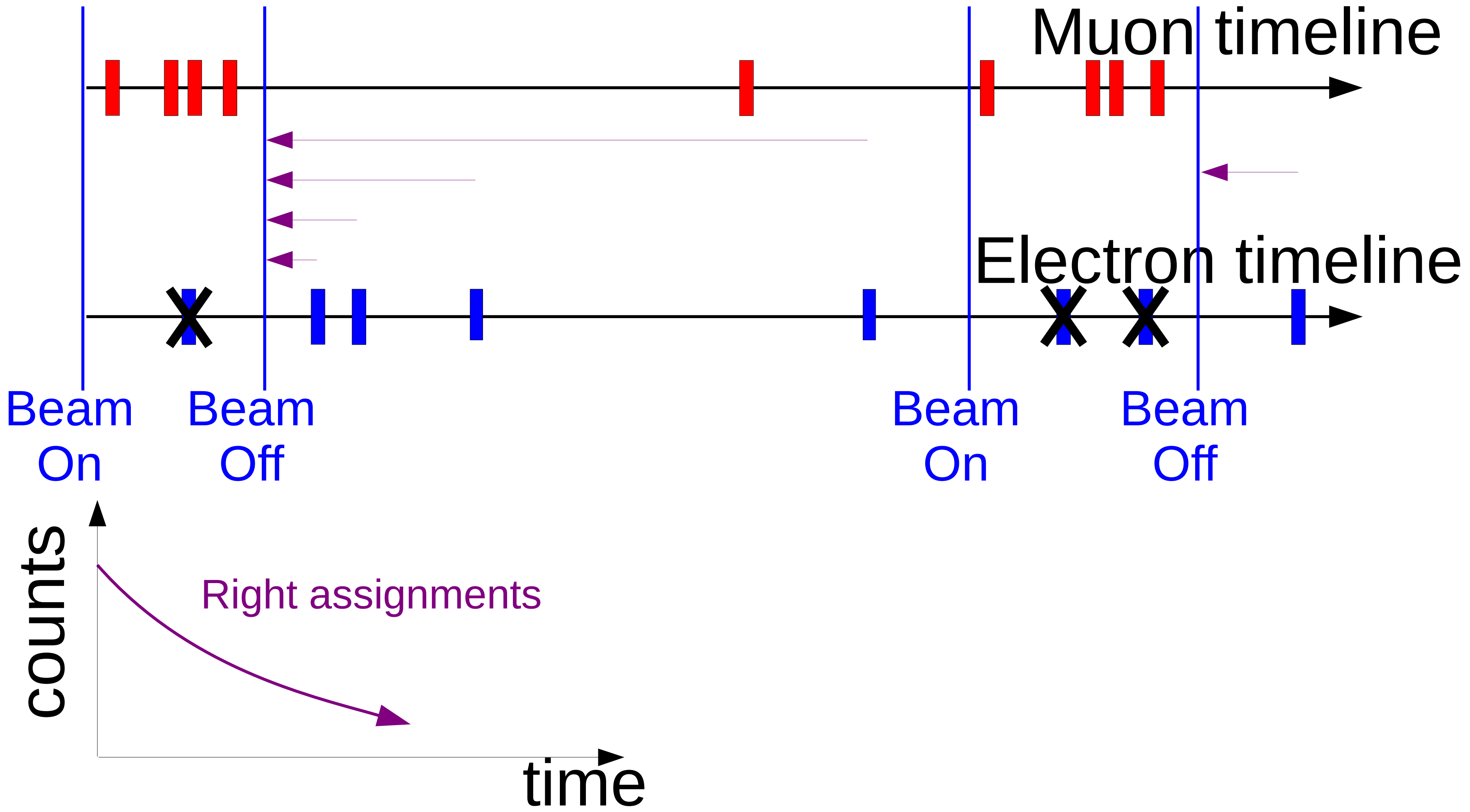
Many-at-once

Need time structured (AC) beam, not a continuous (DC) beam



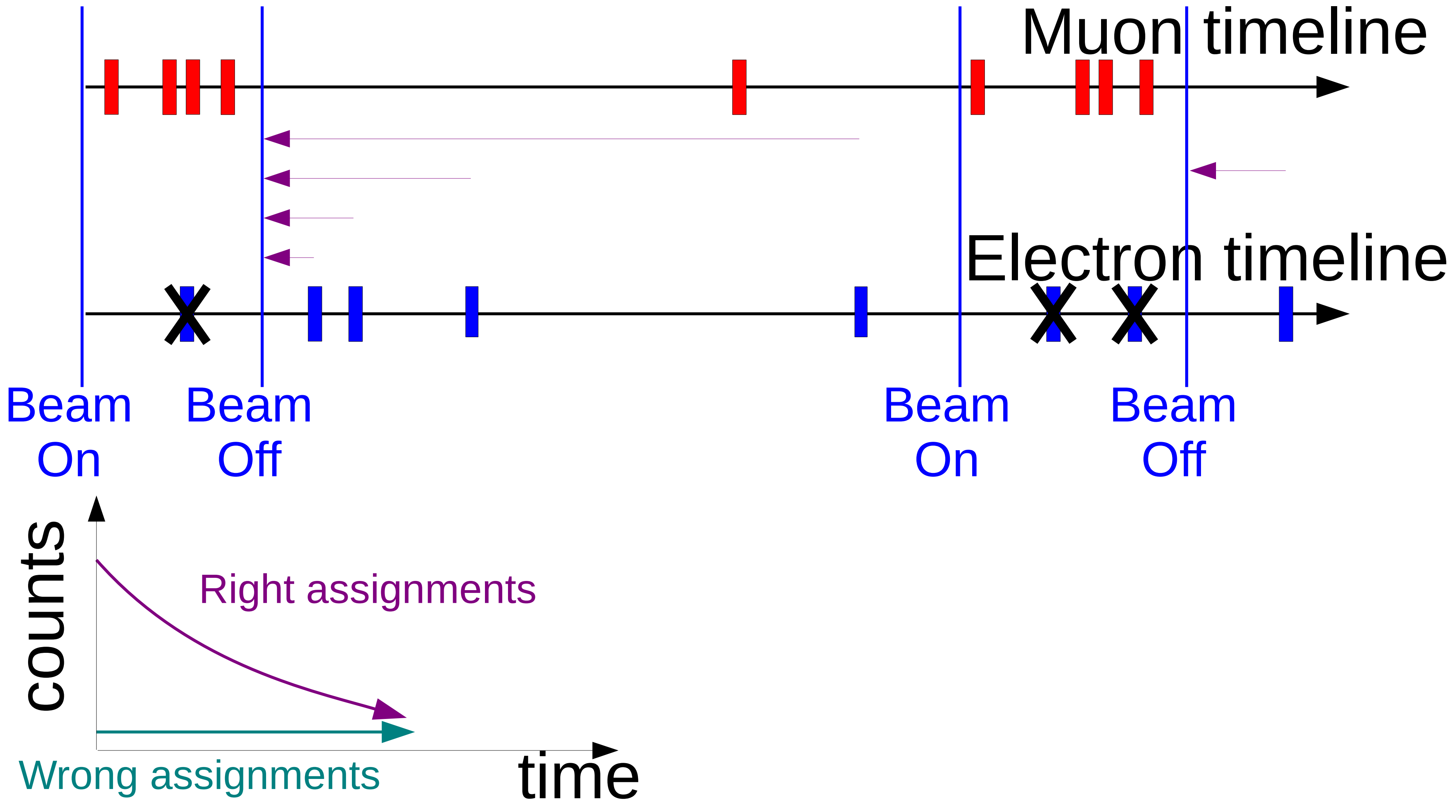
Many-at-once

Need time structured (AC) beam, not a continuous (DC) beam



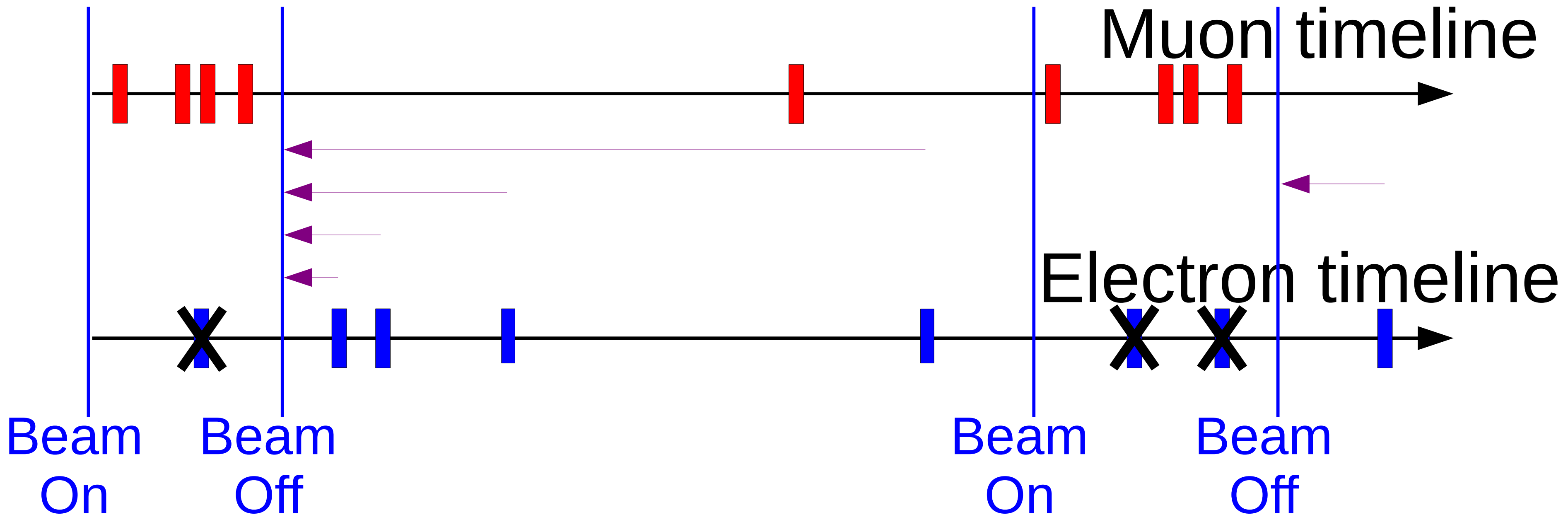
Many-at-once

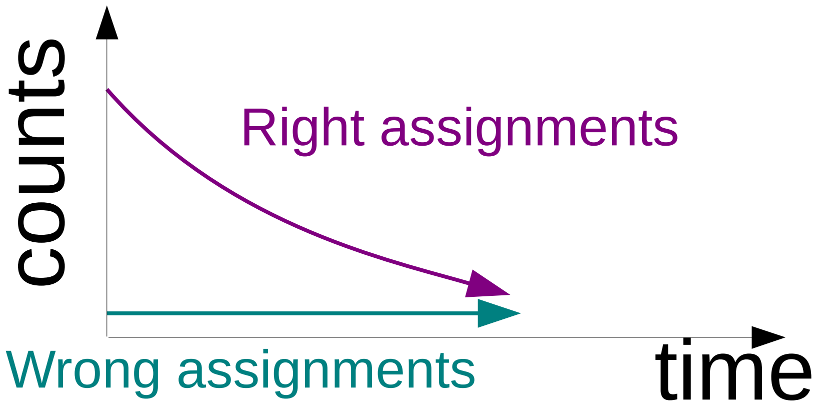
Need time structured (AC) beam, not a continuous (DC) beam



Many-at-once

Need time structured (AC) beam, not a continuous (DC) beam

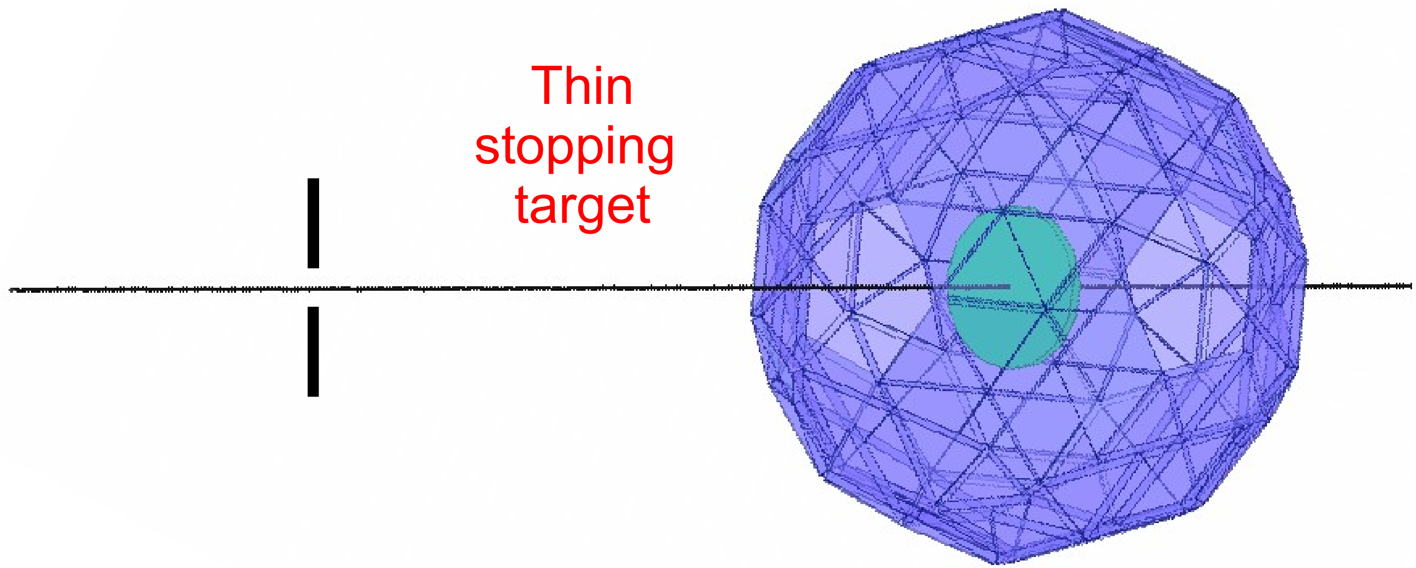




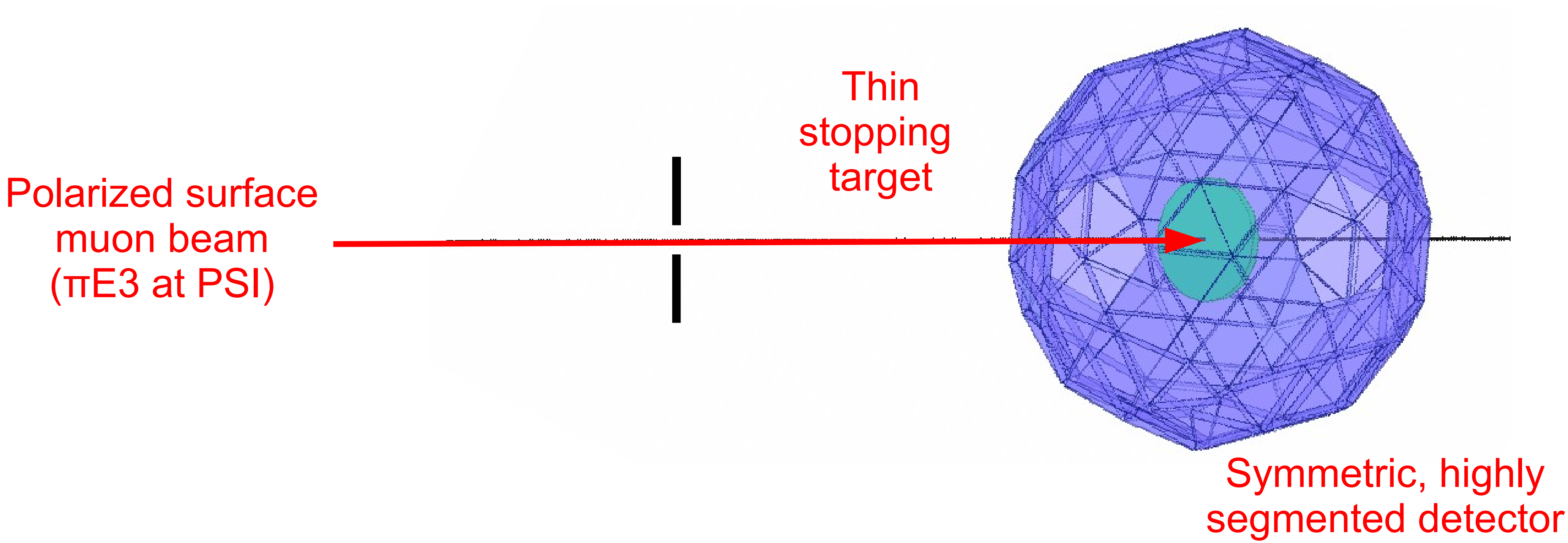
Much higher rates, but much harder experiment R&D and construction

We run in the "many-at-once" mode

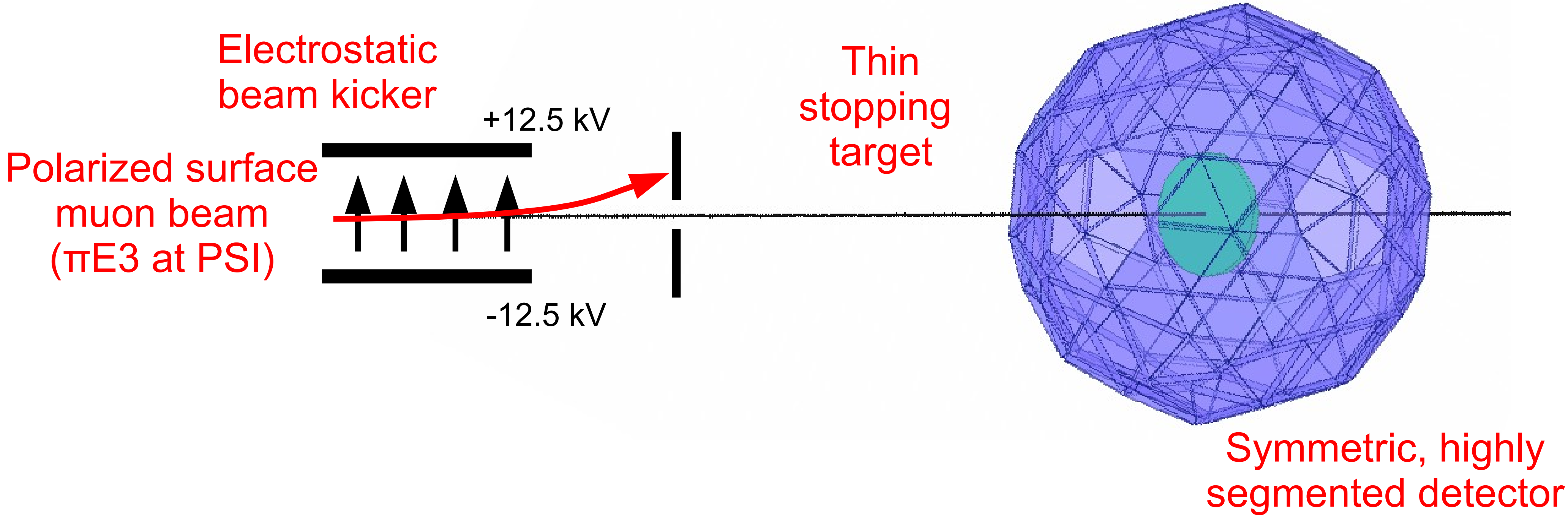
We run in the “many-at-once” mode



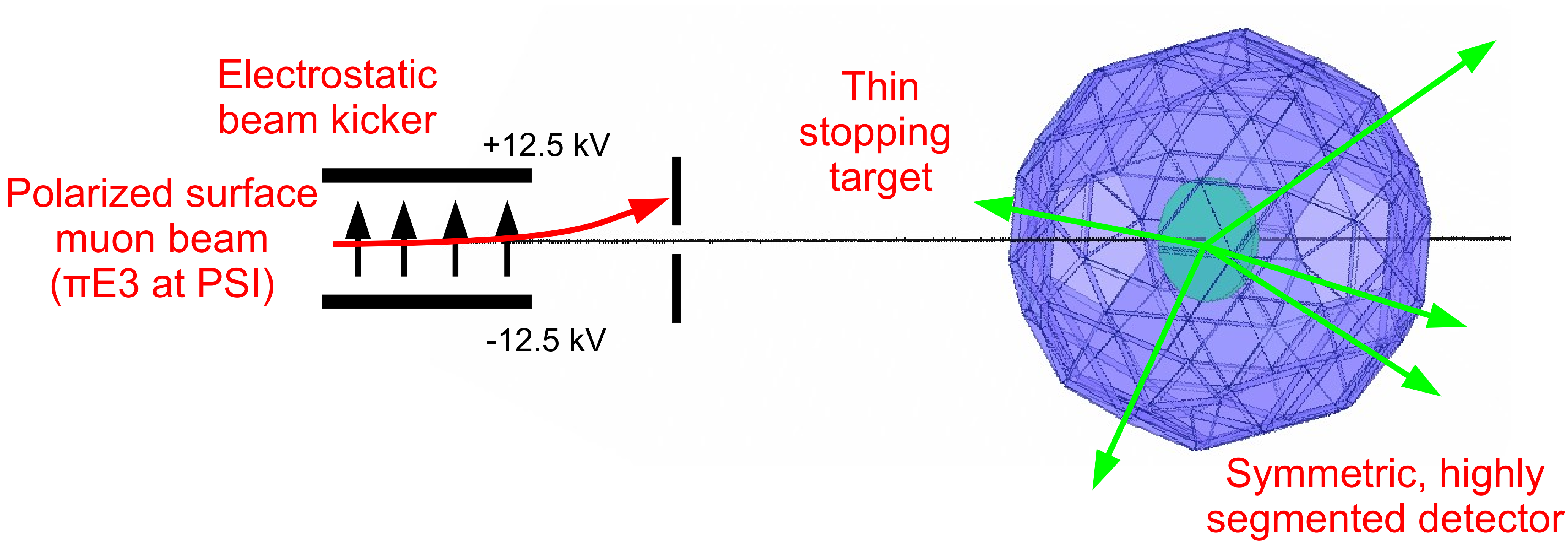
We run in the “many-at-once” mode

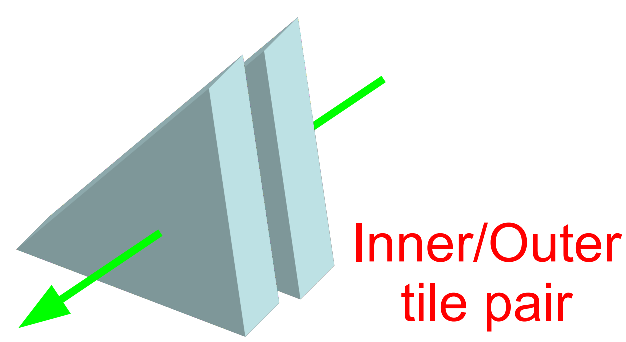


We run in the "many-at-once" mode

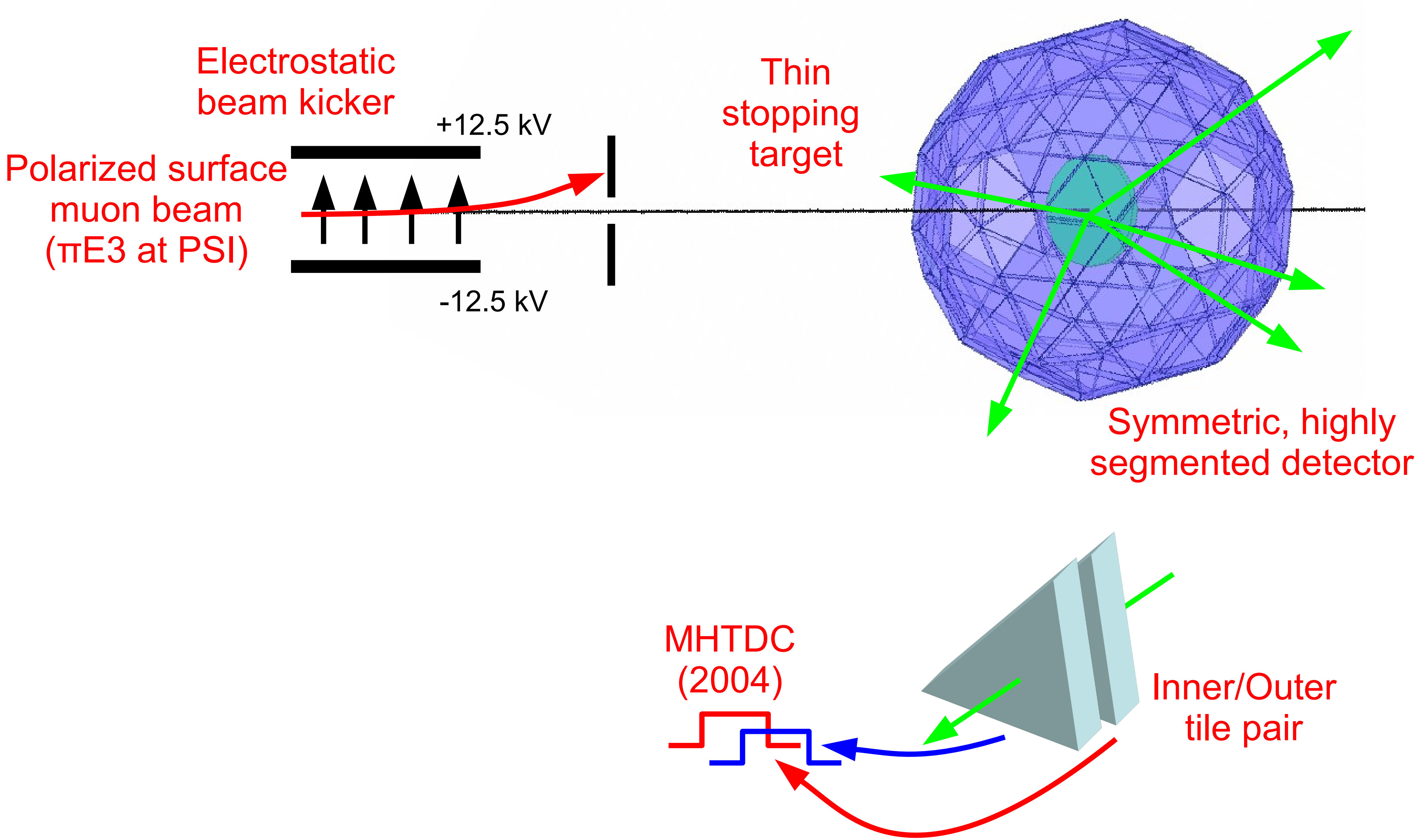


We run in the “many-at-once” mode

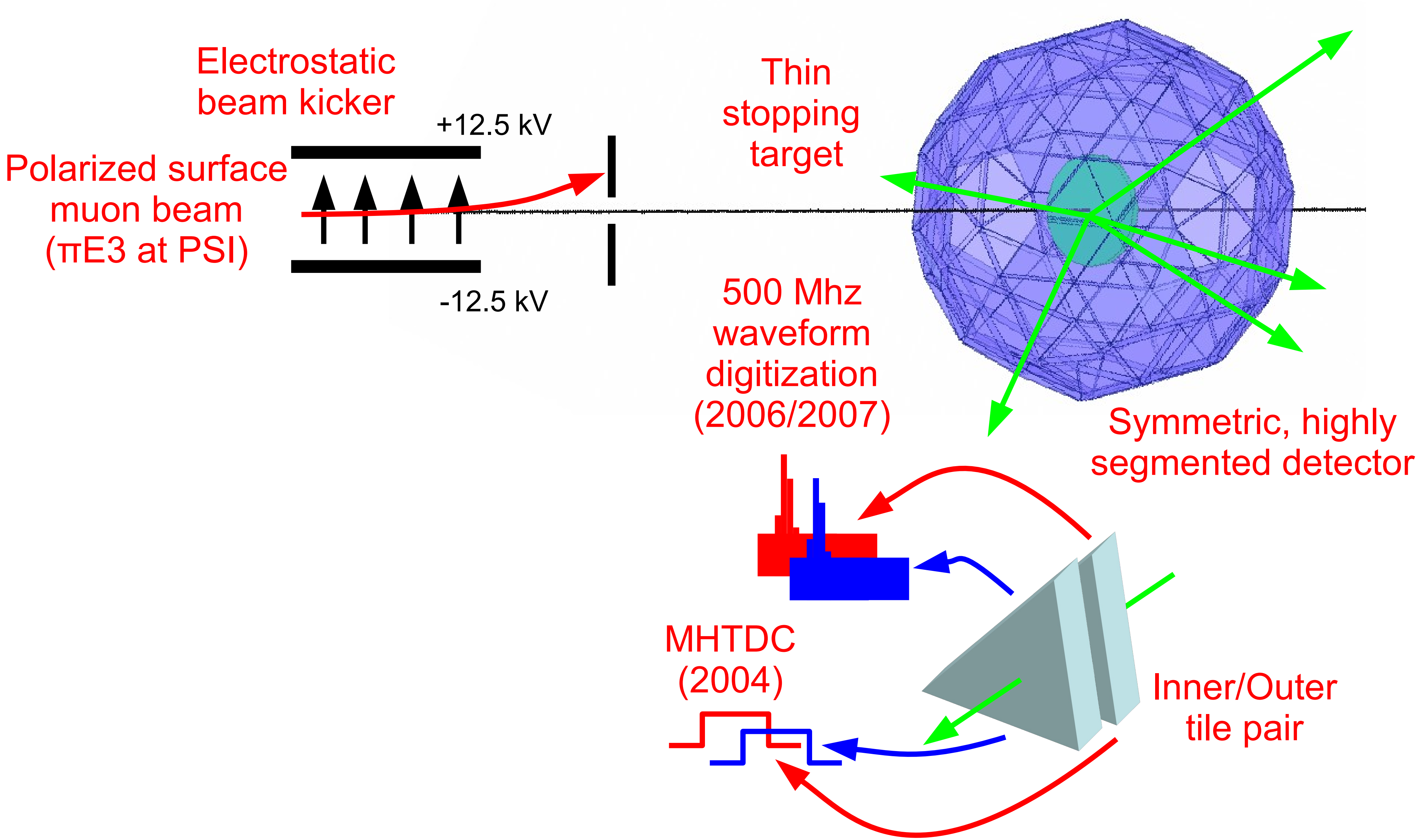




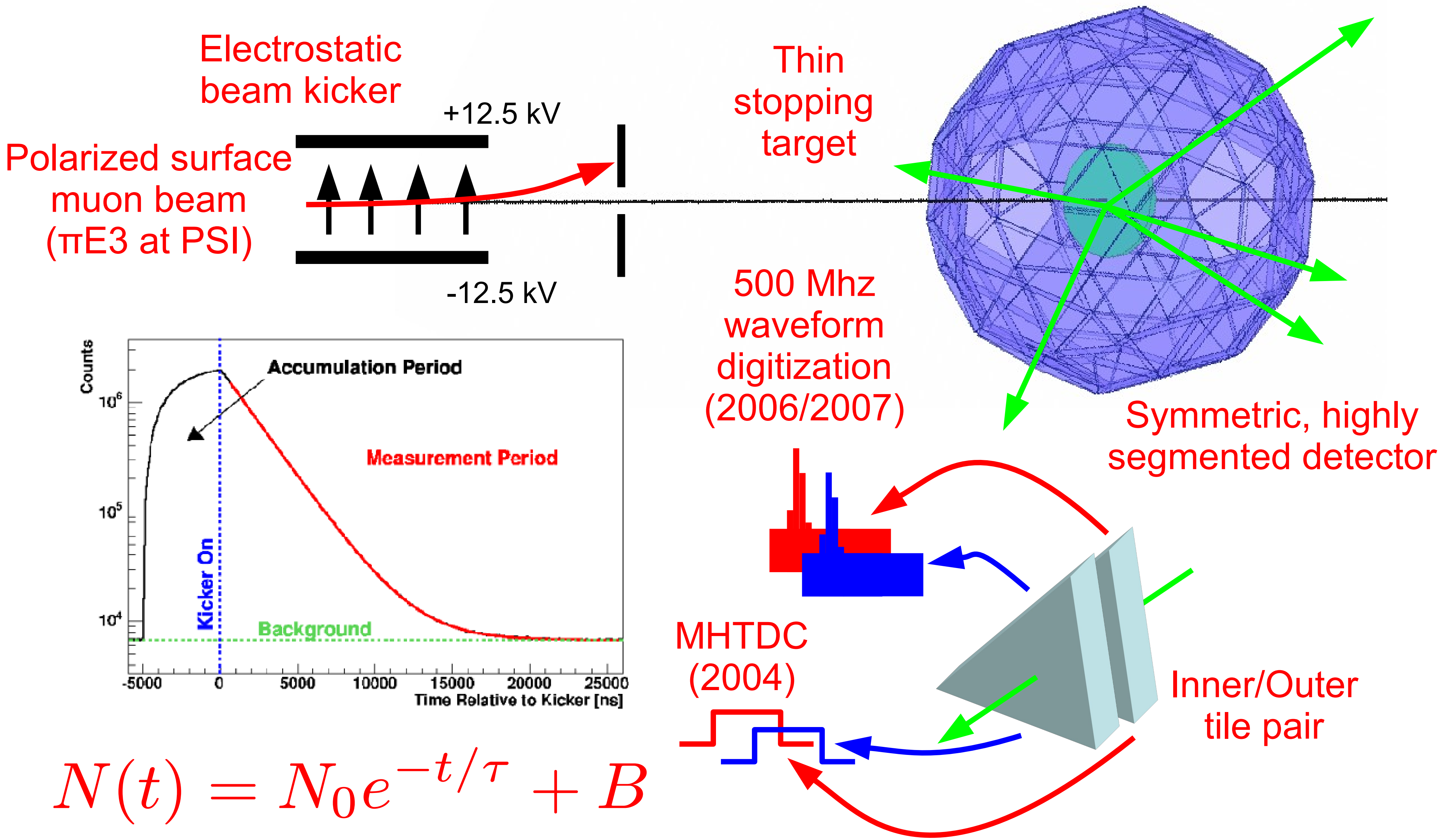
We run in the “many-at-once” mode



We run in the “many-at-once” mode



We run in the “many-at-once” mode

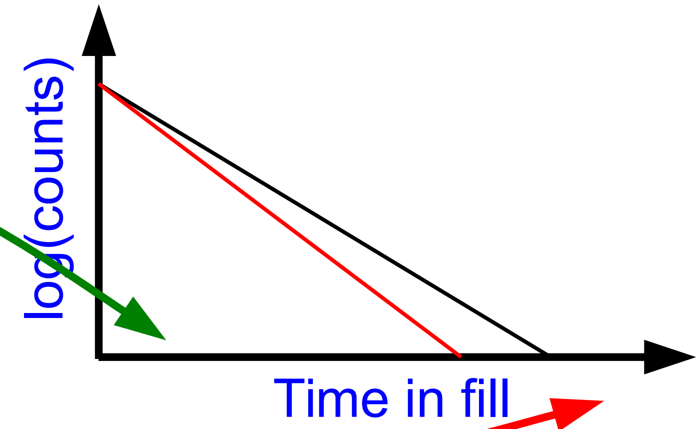


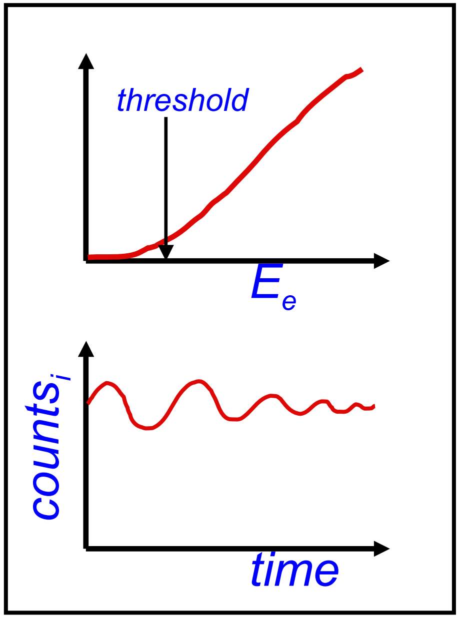
$$N(t) = N_0 e^{-t/\tau} + B$$

Time-dependent systematics are the core concern for a 10^{12} data set

Early-to-late changes, for instance:

- Instrumental issues
  - PMT gains
  - Discriminator threshold walk
  - Kicker voltage sag
  - Pileup
- Physics issues
  - Polarization precession
  - Longitudinal relaxation

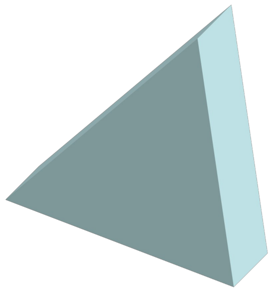




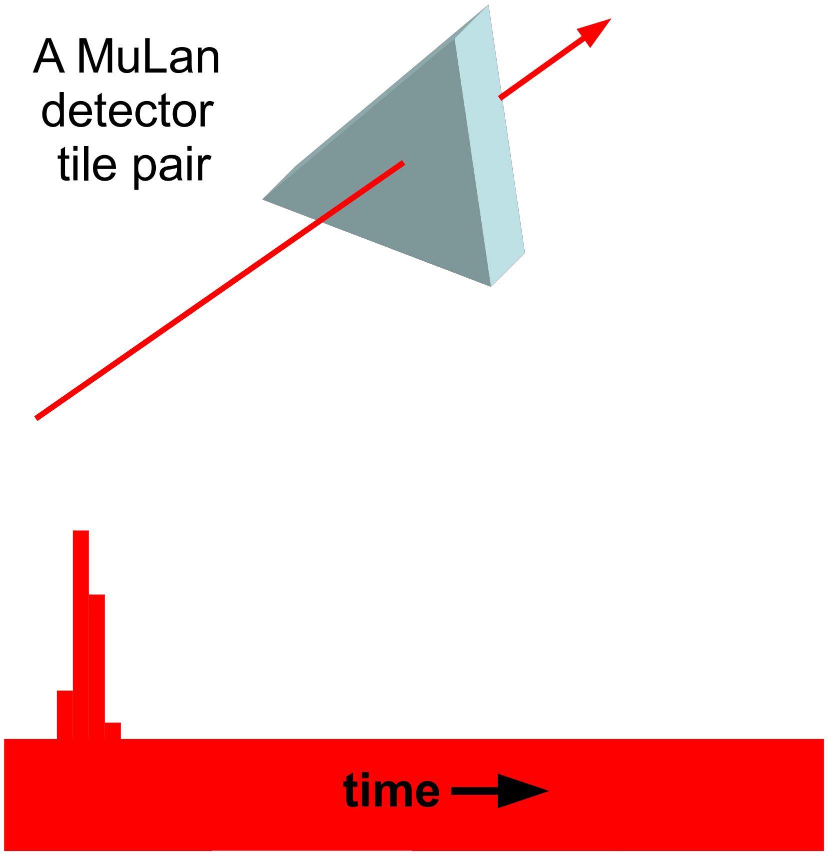
V Tishchenko, et al. Phys Rev D 052003 (2013)

The pileup spectrum can be constructed directly from the data

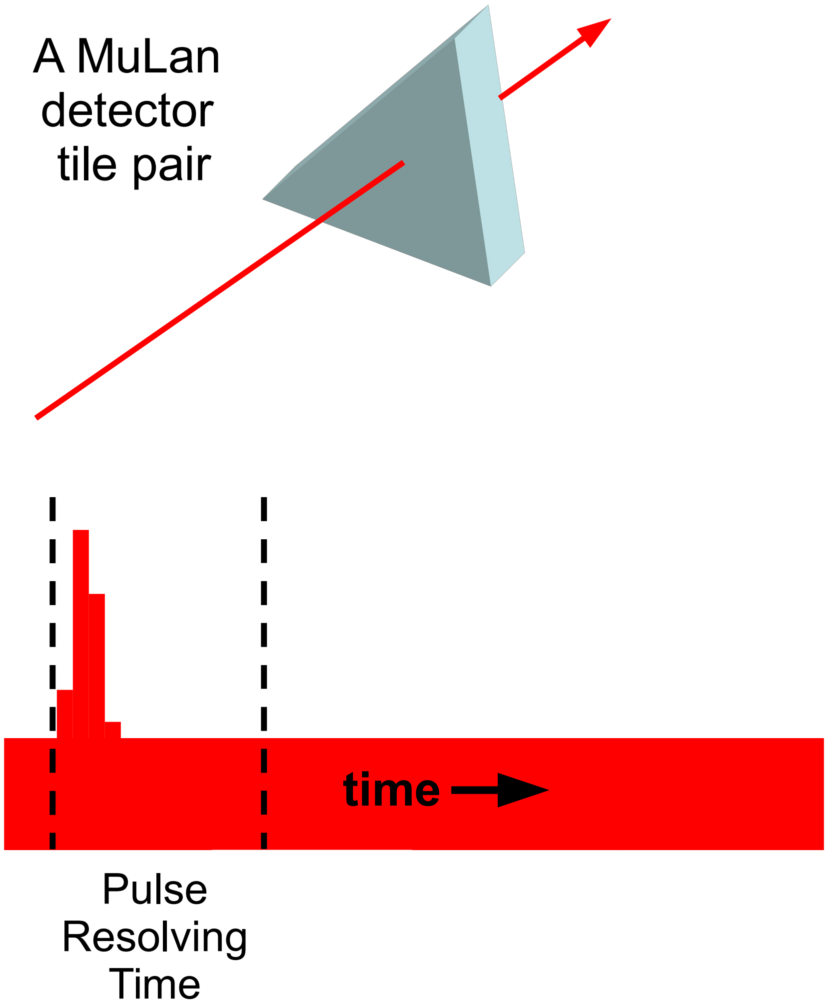
A MuLan detector tile pair



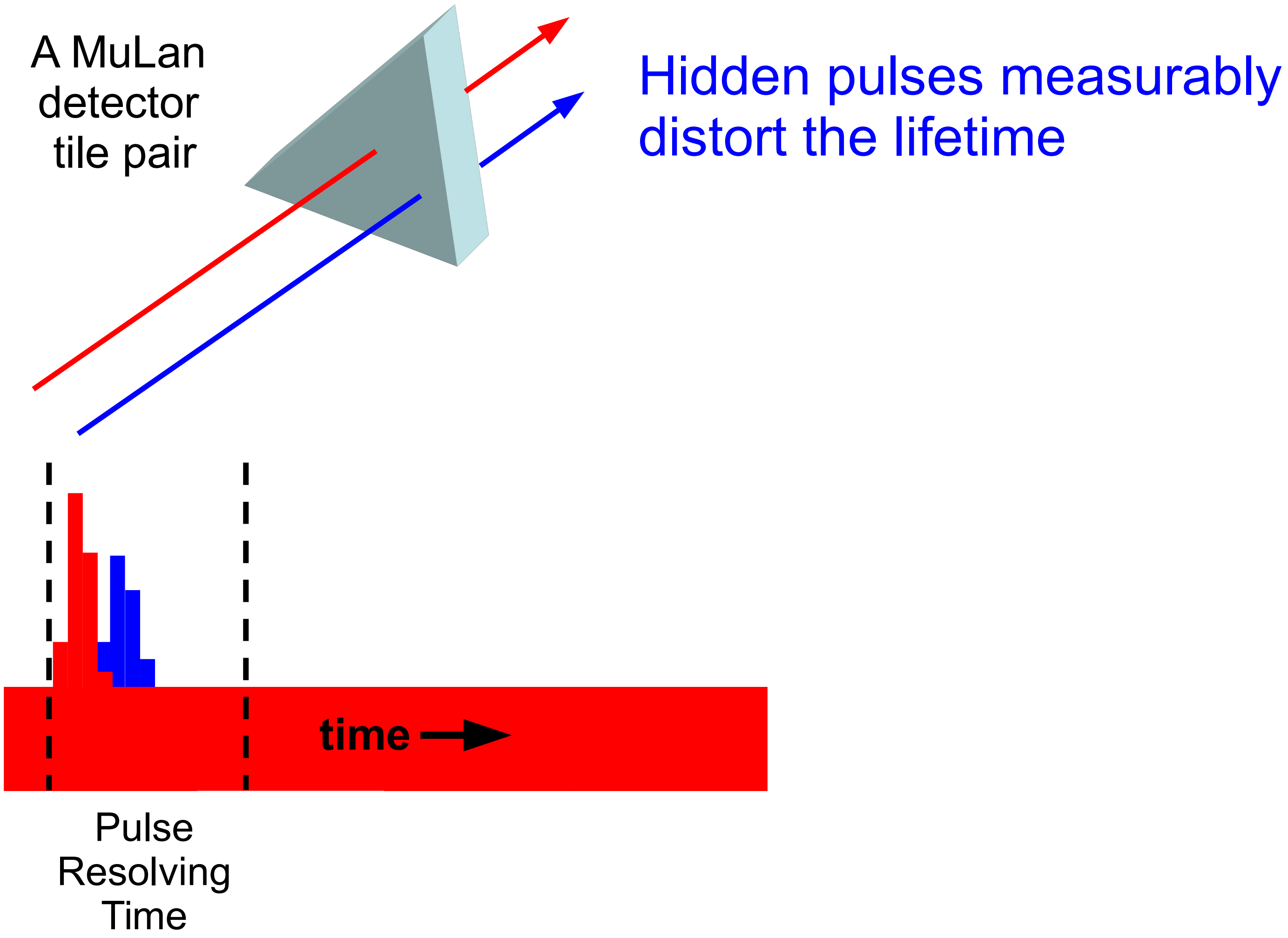
The pileup spectrum can be constructed directly from the data



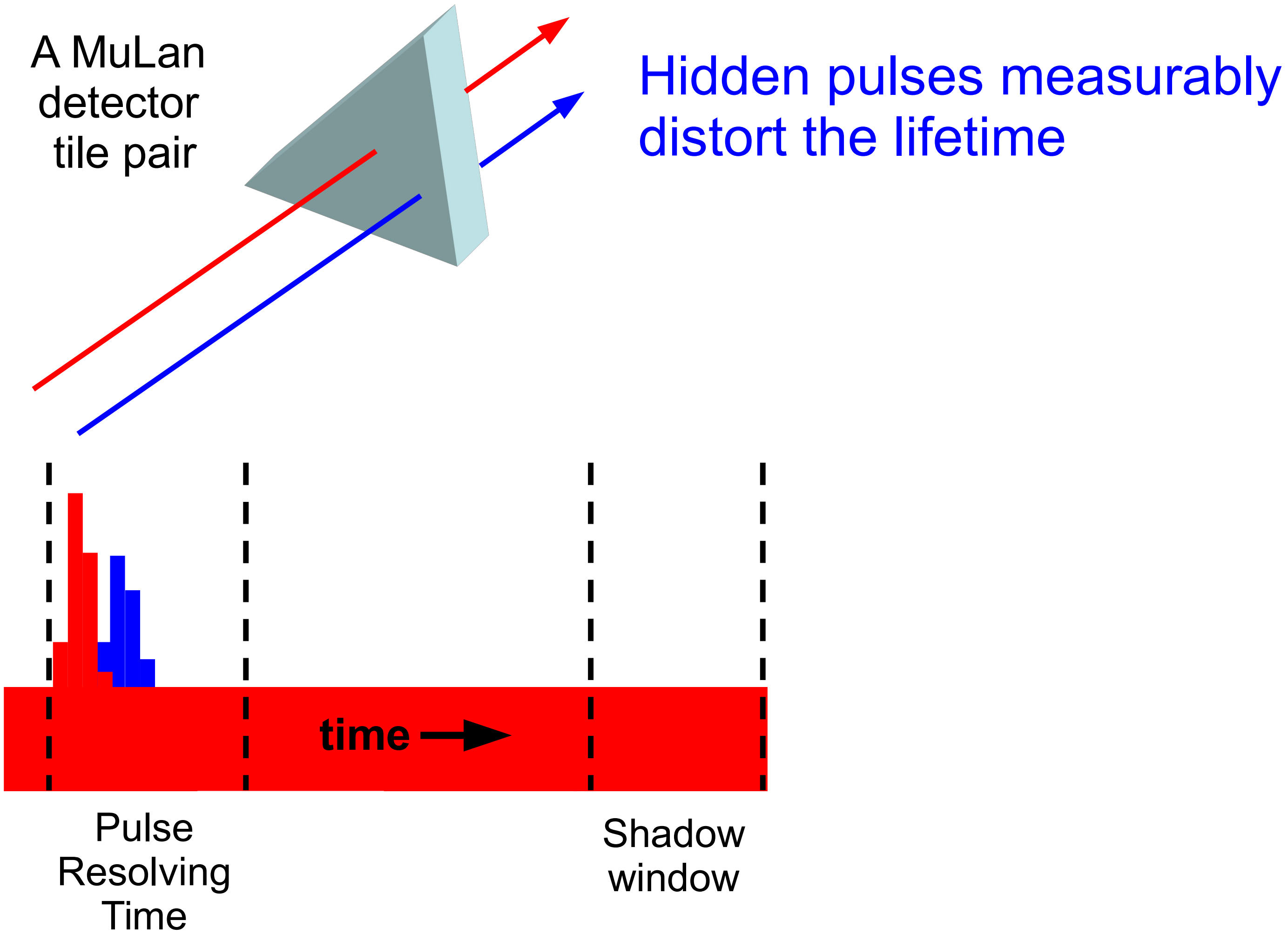
The pileup spectrum can be constructed directly from the data



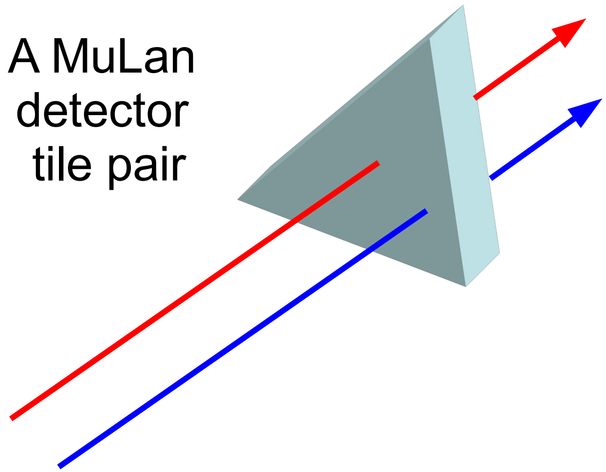
The pileup spectrum can be constructed directly from the data



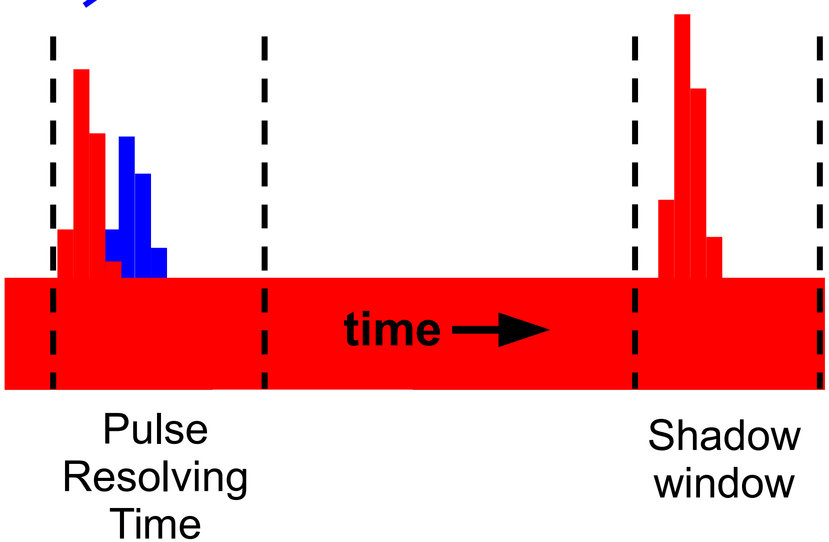
The pileup spectrum can be constructed directly from the data

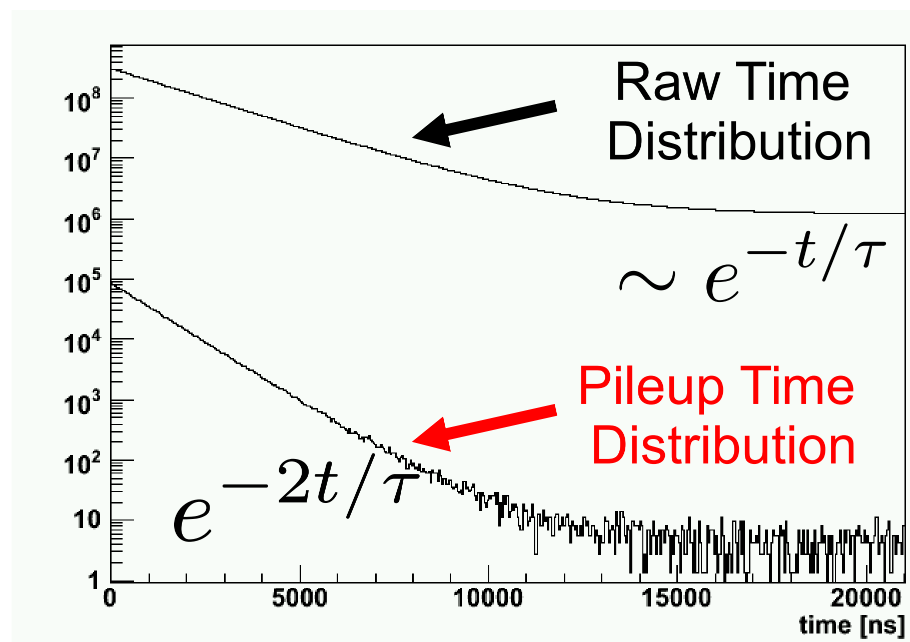


The pileup spectrum can be constructed directly from the data



Hidden pulses measurably distort the lifetime

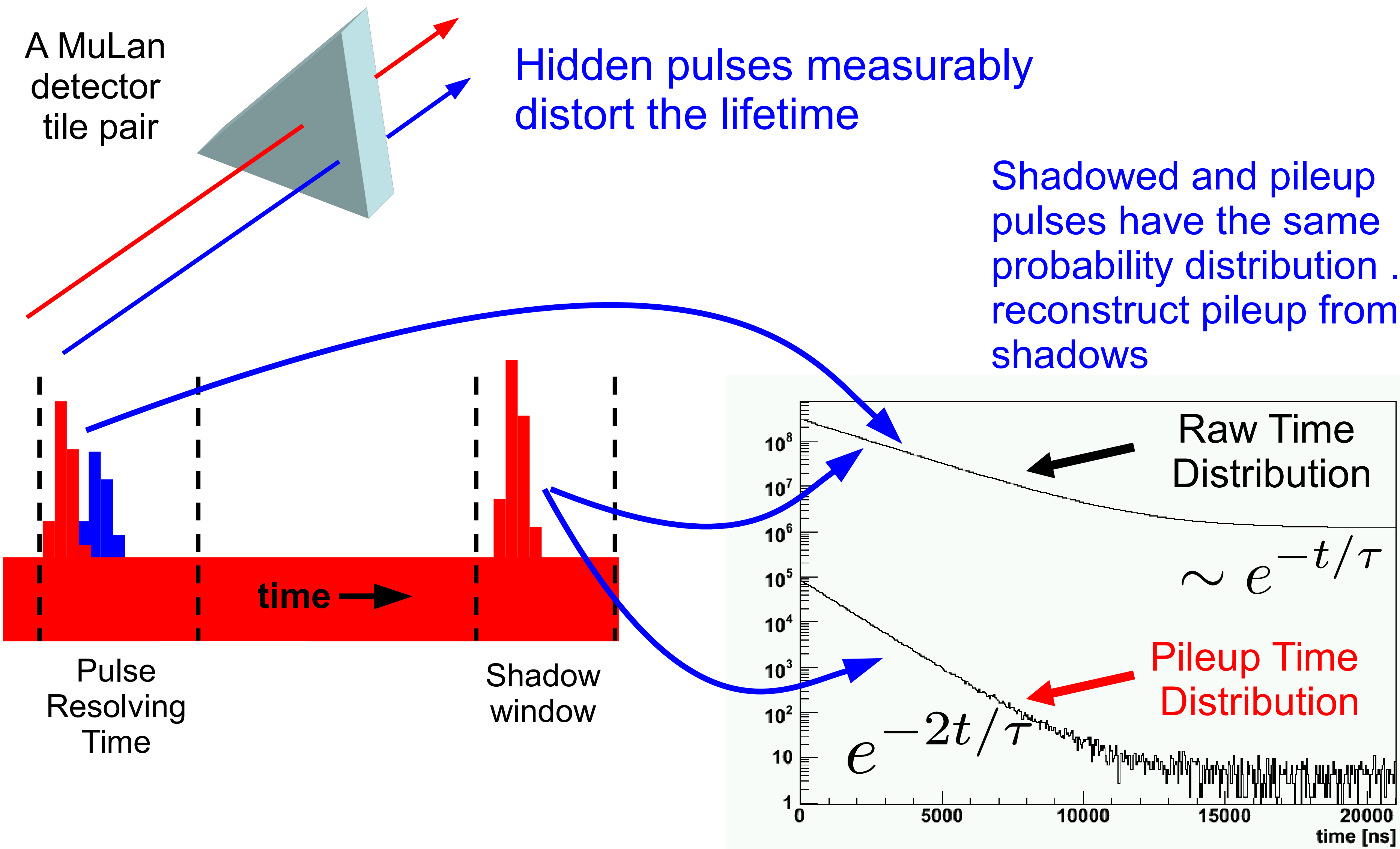




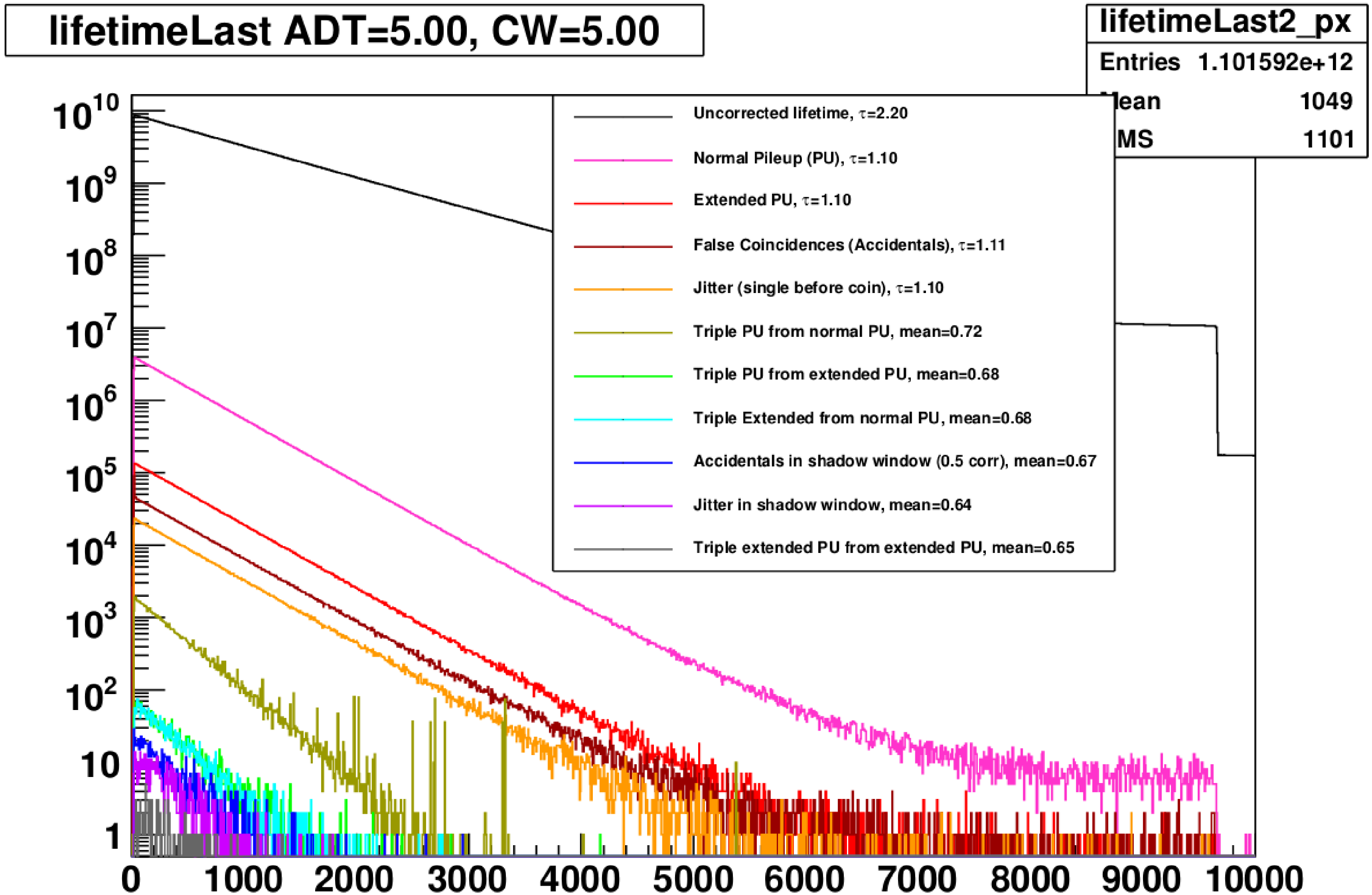
The pileup spectrum can be constructed directly from the data

Hidden pulses measurably distort the lifetime

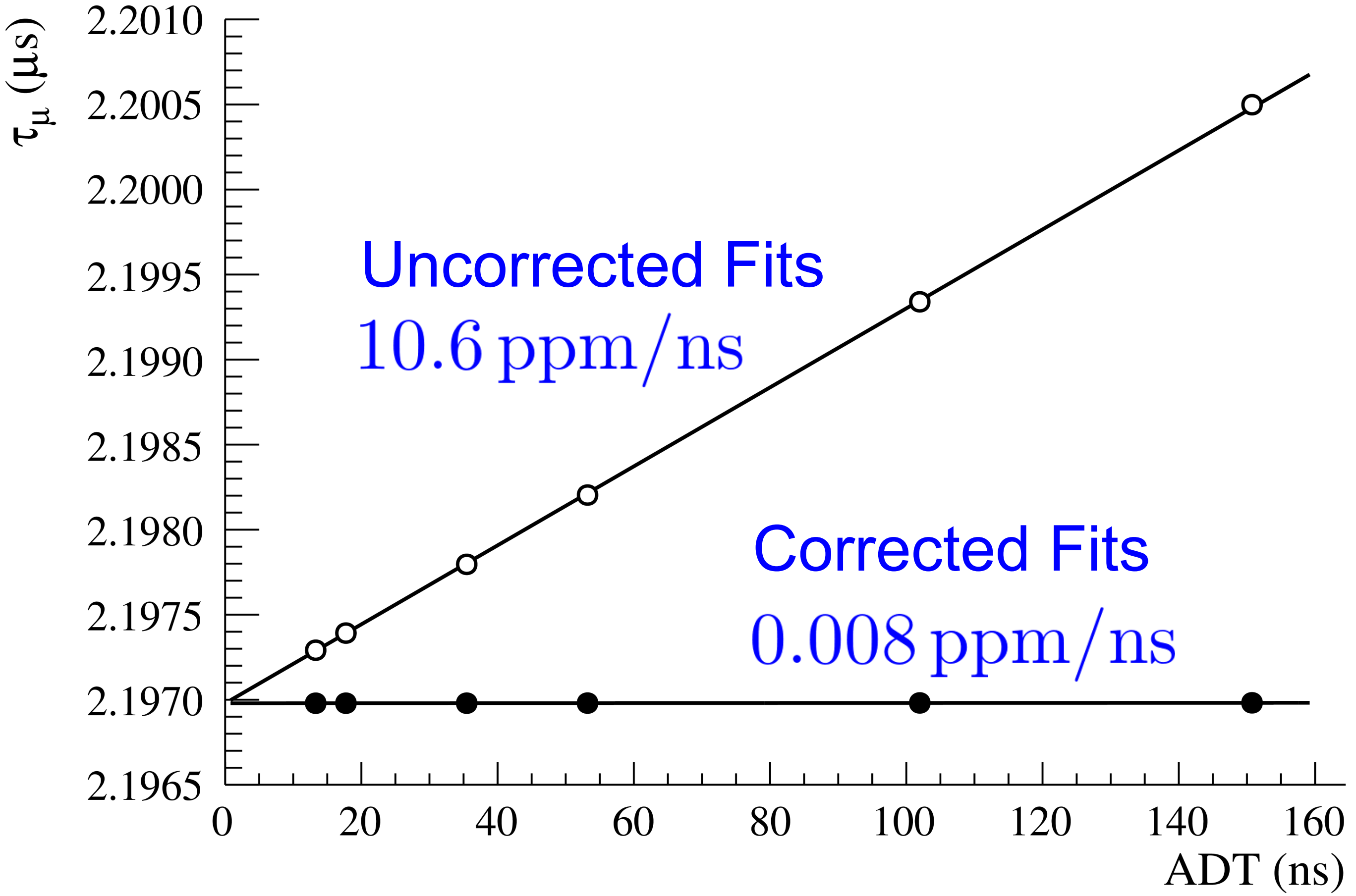
Shadowed and pileup pulses have the same probability distribution ... reconstruct pileup from shadows



For a 1ppm measurement, we have to go well beyond the single event pileup spectrum

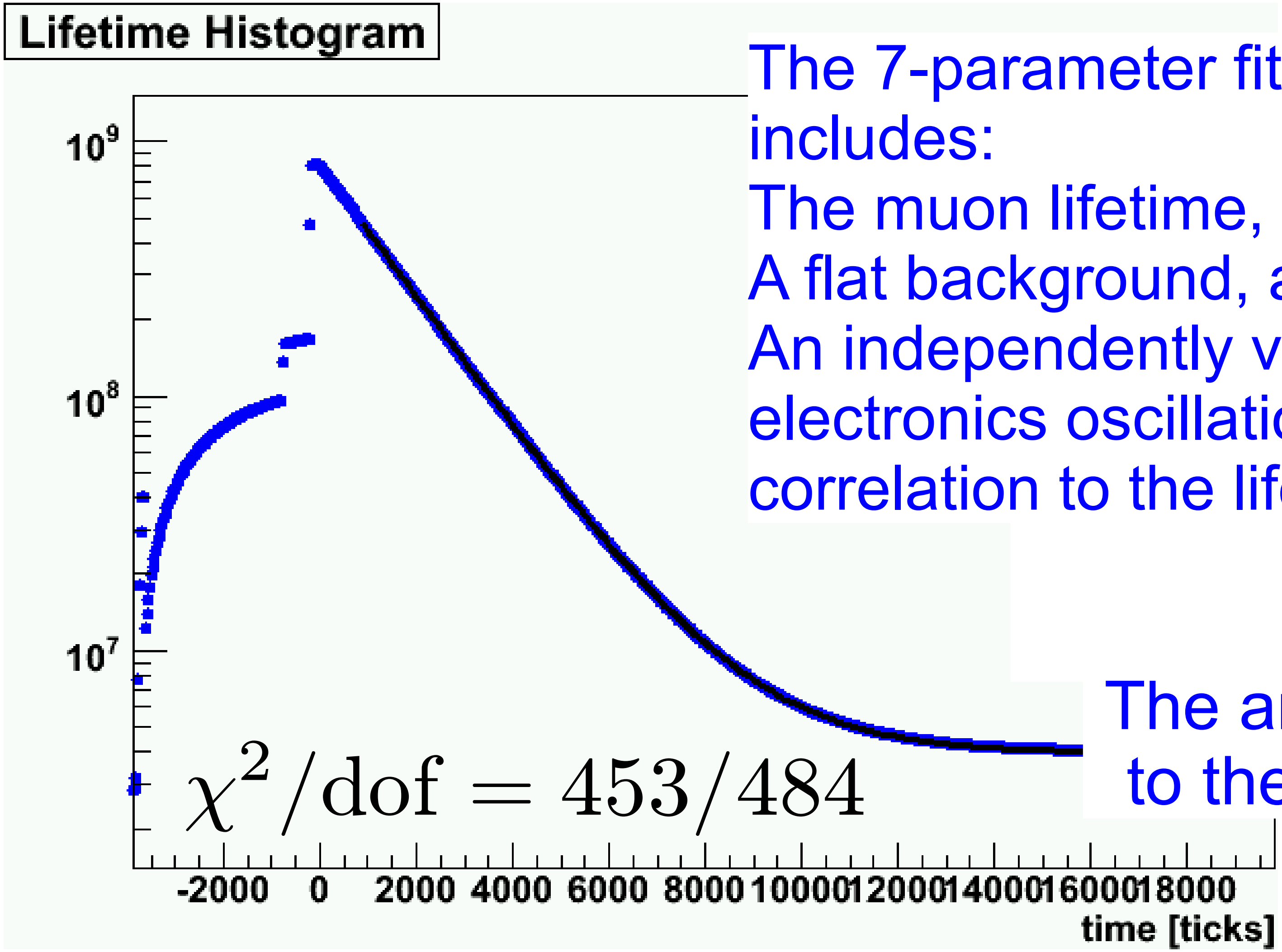


How well does the shadow method correct pileup?



In our final result, we extrapolate to zero resolution time, and apply a systematic to cover the very small residual effect

Analysis of our 2004 Physics run yielded a 11 ppm lifetime measurement



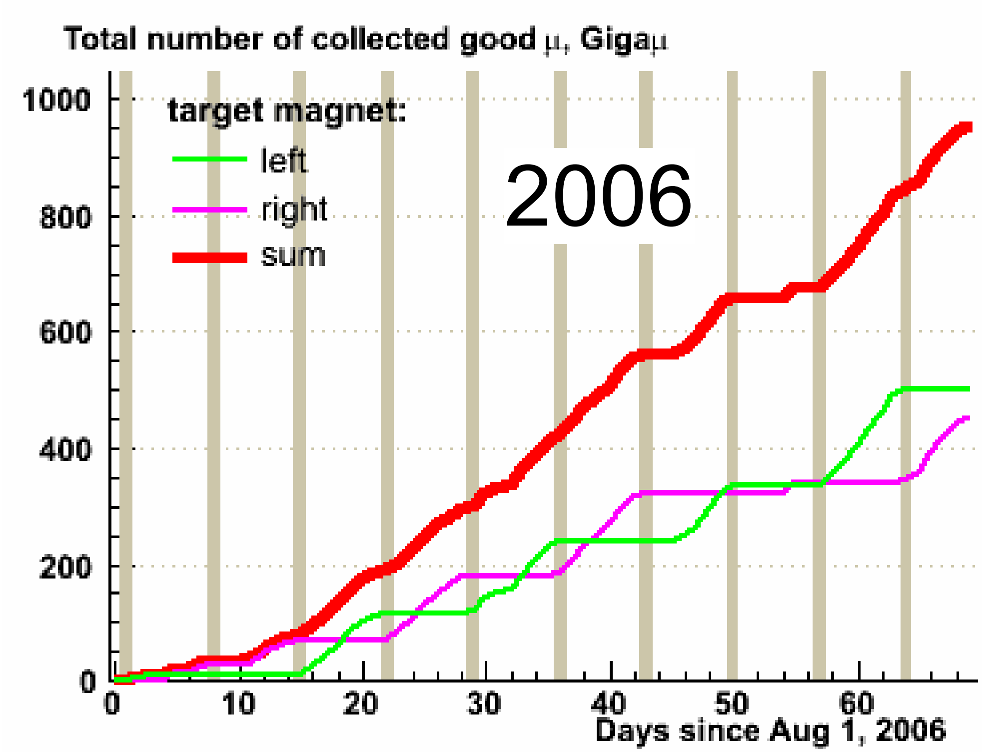
The 7-parameter fit function includes:
The muon lifetime,
A flat background, and
An independently validated electronics oscillation (with low correlation to the lifetime)

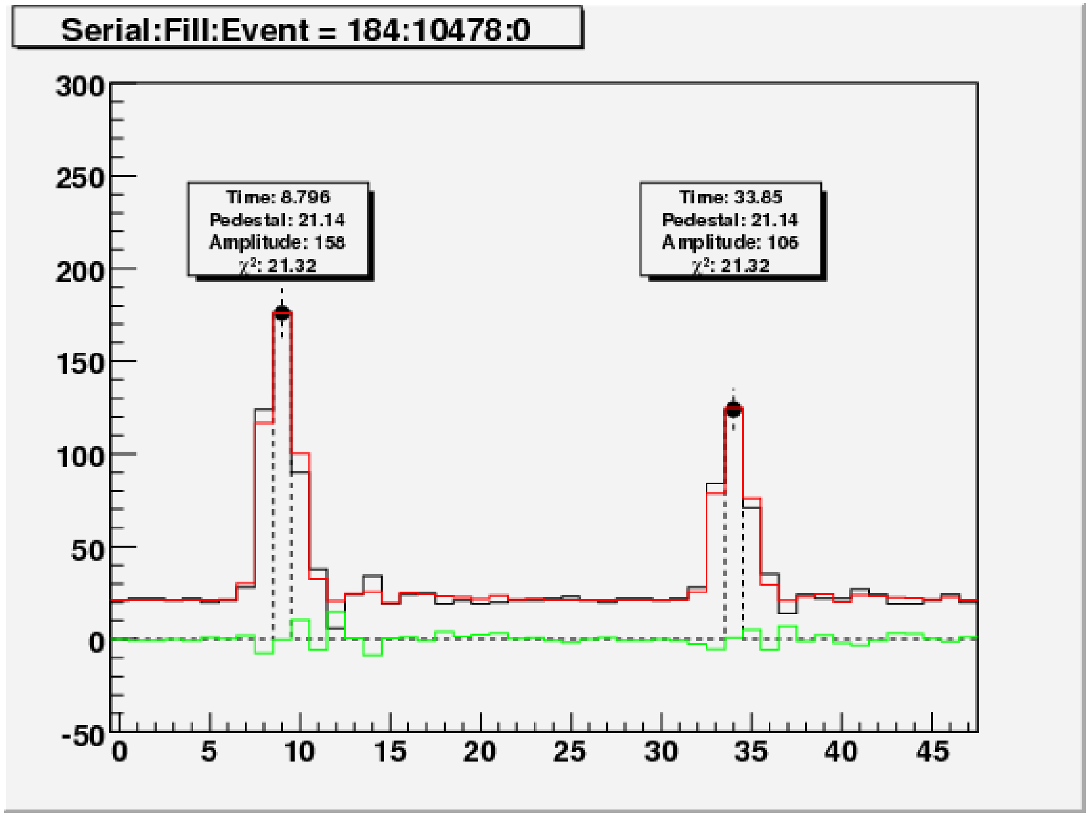
The analyzers are blind to the clock frequency

MuLan Collaboration, Phys. Rev. Lett. 99, 032001 (2007)

We engaged in extensive analysis of our 2006 and 2007 data sets ...

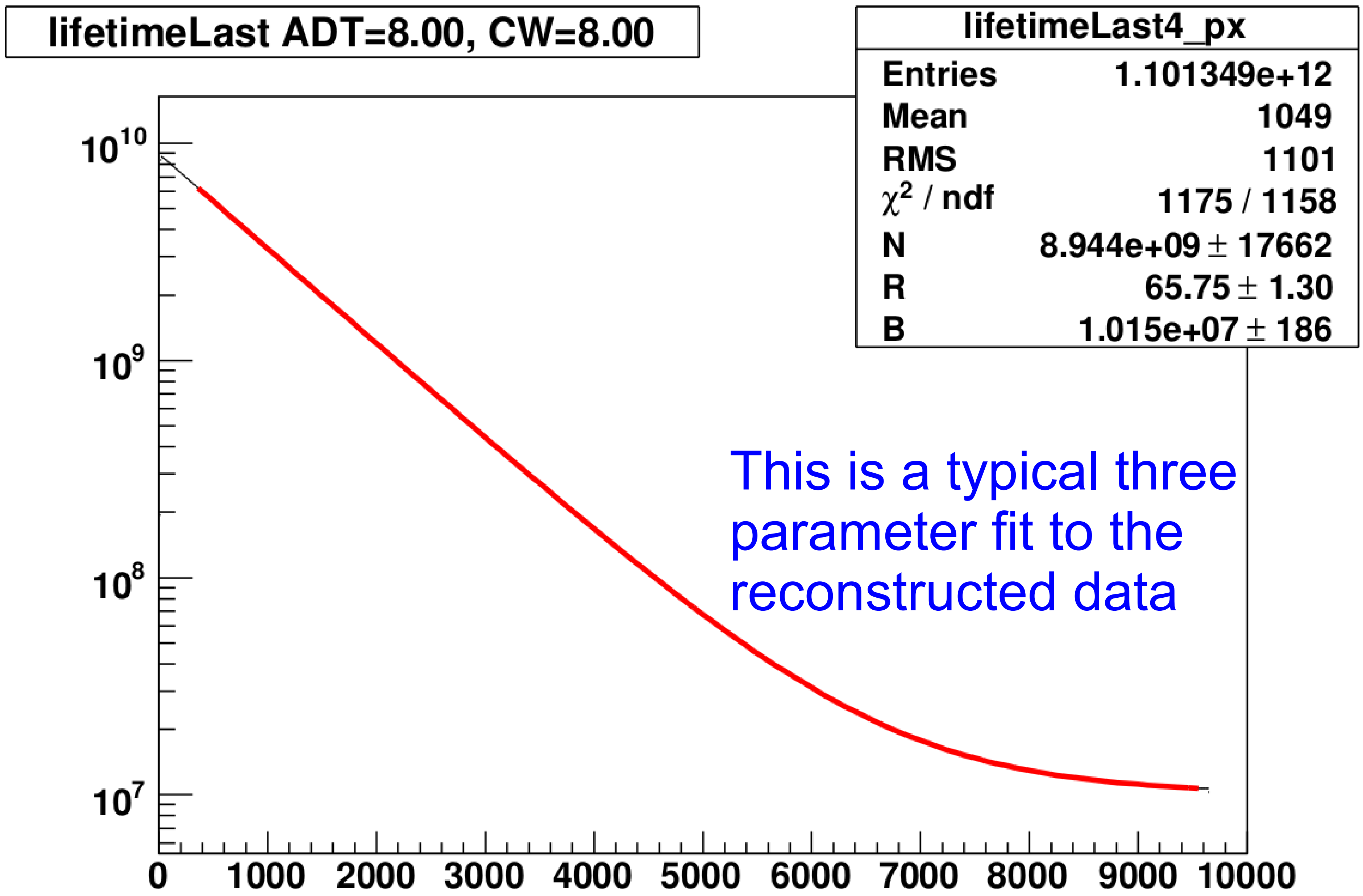
Nearly 10^{12} events on tape for each period...





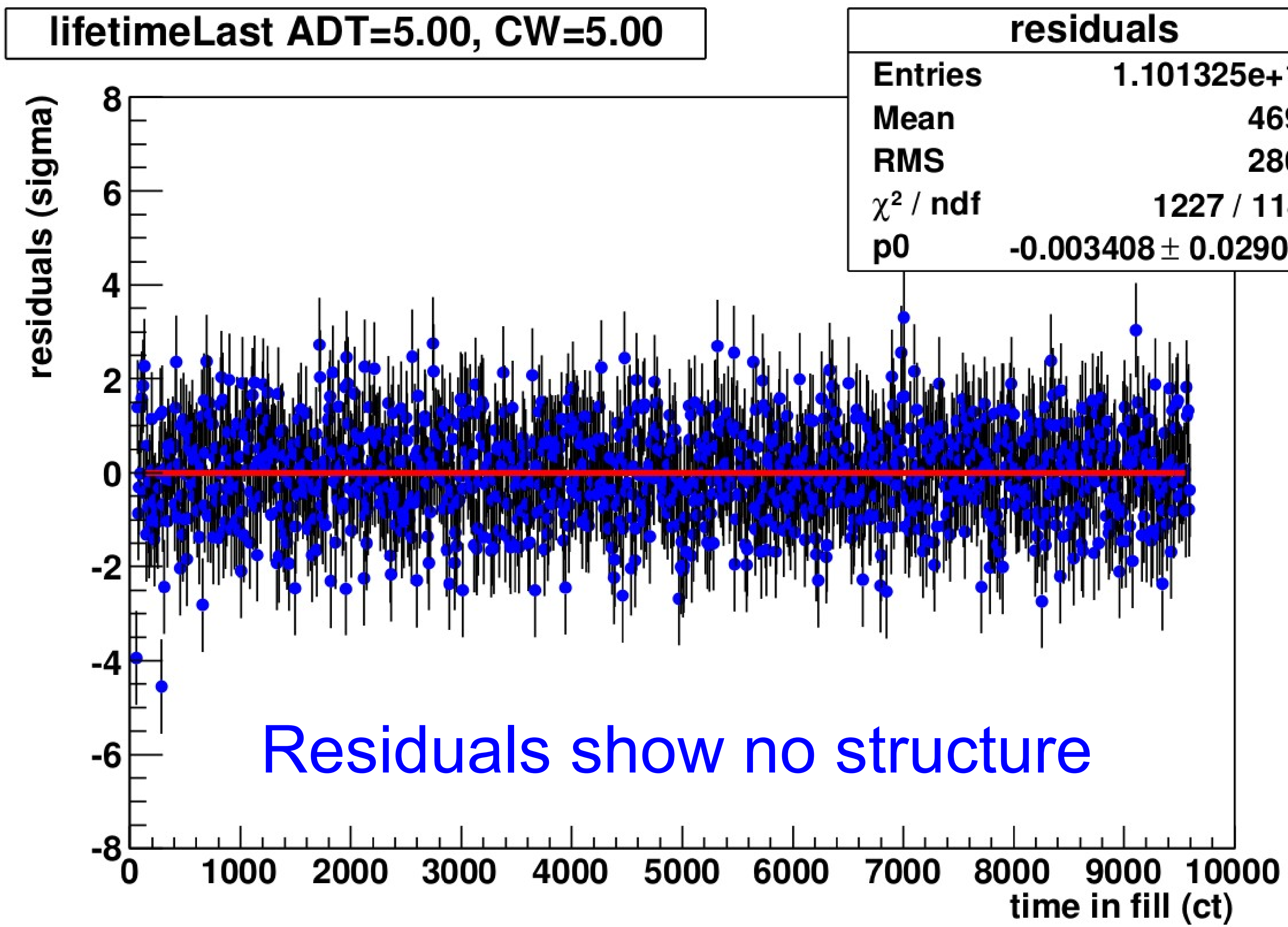
... while new electronics and analysis techniques greatly reduced systematics over 2004.

Lifetime fits

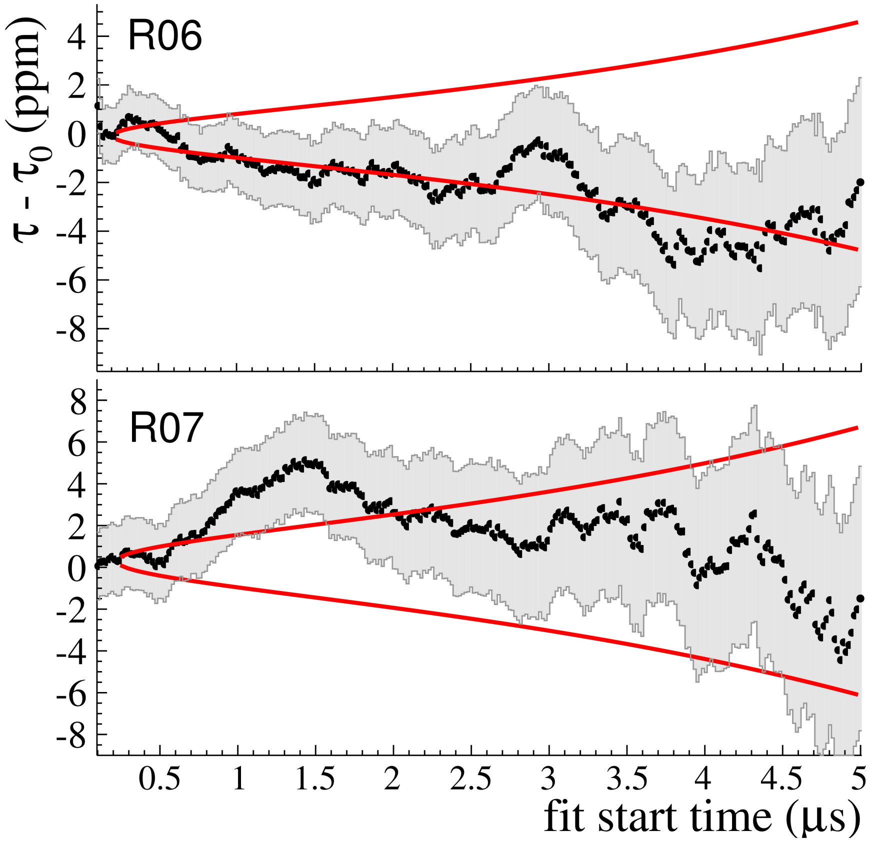


This is a typical three parameter fit to the reconstructed data

Lifetime fits

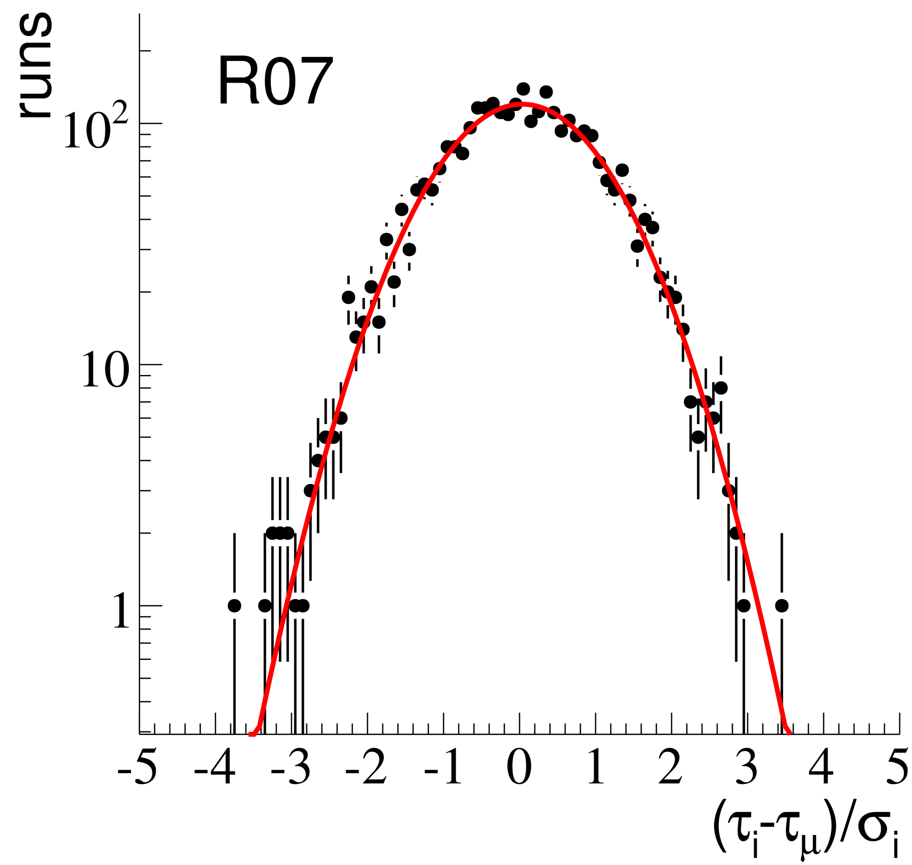


We studied a significant number of data subsets for lifetime consistency across various conditions



Fit start time scans show no evidence of missing long time scale components

The lifetimes measured by individual detector pairs appear statistically consistent



We believe our systematics are well understood for both run periods

Uncertainty	R06 (ppm)	R07 (ppm)
Kicker stability	0.20	0.07
μSR distortions	0.10	0.20
Pulse pileup	0.20	
Gain variations	0.25	
Upstream stops	0.10	
Timing pick-off stability	0.12	
Master clock calibration	0.03	
Combined systematic uncertainty	0.42	0.42
Statistical uncertainty	1.14	1.68

The lifetime results for our three run periods are entirely consistent

$$\tau_\mu^{\mathrm{R06}} = 2\,196\,979.9 \pm 2.5(\mathrm{stat}) \pm 0.9(\mathrm{syst})\,\mathrm{ps}$$

$$\tau_\mu^{\mathrm{R07}} = 2\,196\,981.2 \pm 3.7(\mathrm{stat}) \pm 0.9(\mathrm{syst})\,\mathrm{ps}$$

After properly accounting for the correlated systematics, the final combined MuLan result is

$$\tau_\mu^{\mathrm{MuLan}} = 2\,196\,980.3 \pm 2.1(\mathrm{stat}) \pm 0.7(\mathrm{syst})\,\mathrm{ps}$$

The lifetime results for our three run periods are entirely consistent

$$\tau_\mu^{\rm R06} = 2\,196\,979.9 \pm 2.5({\rm stat}) \pm 0.9({\rm syst})\,{\rm ps}$$

$$\tau_\mu^{\rm R07} = 2\,196\,981.2 \pm 3.7({\rm stat}) \pm 0.9({\rm syst})\,{\rm ps}$$

After properly accounting for the correlated systematics, the final combined MuLan result is

$$\tau_\mu^{\rm MuLan} = 2\,196\,980.3 \pm 2.1({\rm stat}) \pm 0.7({\rm syst})\,{\rm ps}$$

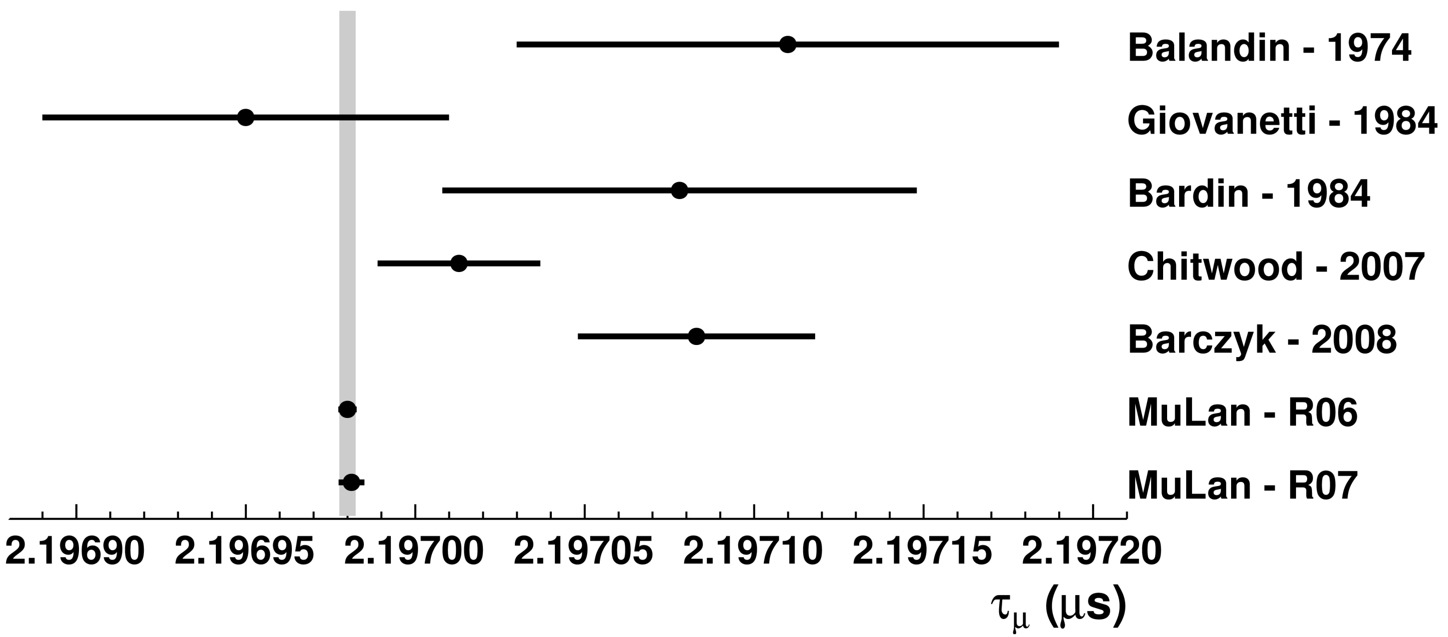
$$\pm 2.2\,{\rm ps} \longrightarrow 1.0\,{\rm ppm}$$

Our combined result dominates the world average

Measured lifetime (μs)	Reference	Publication year
$2.196\ 9803 \pm 0.000\ 0022$	R06+R07	
$2.196\ 9799 \pm 0.000\ 0027$	R06	
$2.196\ 9812 \pm 0.000\ 0038$	R07	
$2.197\ 083 \pm 0.000\ 035$	Barczyk	2008
$2.197\ 013 \pm 0.000\ 024$	Chitwood	2007
$2.197\ 078 \pm 0.000\ 073$	Bardin	1984
$2.196\ 95 \pm 0.000\ 06$	Giovanetti	1984
$2.197\ 11 \pm 0.000\ 08$	Balandin	1974
$2.197\ 3 \pm 0.000\ 3$	Duclos	1973

$$\tau_\mu^{\mathrm{PDG}} = 2\,196\,981.1 \pm 2.2\,\mathrm{ps}$$

There is some tension with the Barczyk result (FAST) that drives the increased error bar in the PDG average.



Our motivation, of course, is extracting the Fermi Constant

Assuming a pure V-A structure of the weak interactions, we can extract Fermi's constant by inverting:

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}\left(1 + \Delta q^{(0)} + \Delta q^{(1)} + \Delta q^{(2)}\right)$$

Phase space

First order corrections

Second order corrections

$$G_F^{\mathrm{MuLan}} = 1.166\,378\,7(6) \times 10^{-5}\,\mathrm{GeV}^{-2}$$

$0.5\,\mathrm{ppm}$

MuLan was systematics limited … could we do better at a future facility?

Uncertainty	R06 (ppm)	R07 (ppm)
Kicker stability	0.20	0.07
μSR distortions	0.10	0.20
Pulse pileup	$\boxed{0.20}$	
Gain variations	$\boxed{0.25}$	
Upstream stops	0.10	
Timing pick-off stability	$\boxed{0.12}$	
Master clock calibration	0.03	
Combined systematic uncertainty	0.42	0.42
Statistical uncertainty	1.14	1.68

MuLan was systematics limited … could we do better at a future facility?

Uncertainty	R06 (ppm)	R07 (ppm)
Kicker stability	0.20	0.07
μSR distortions	0.10	0.20
Pulse pileup	$\boxed{0.20}$	
Gain variations	$\boxed{0.25}$	
Upstream stops	0.10	
Timing pick-off stability	$\boxed{0.12}$	
Master clock calibration	0.03	
Combined systematic uncertainty	0.42	0.42
Statistical uncertainty	1.14	1.68

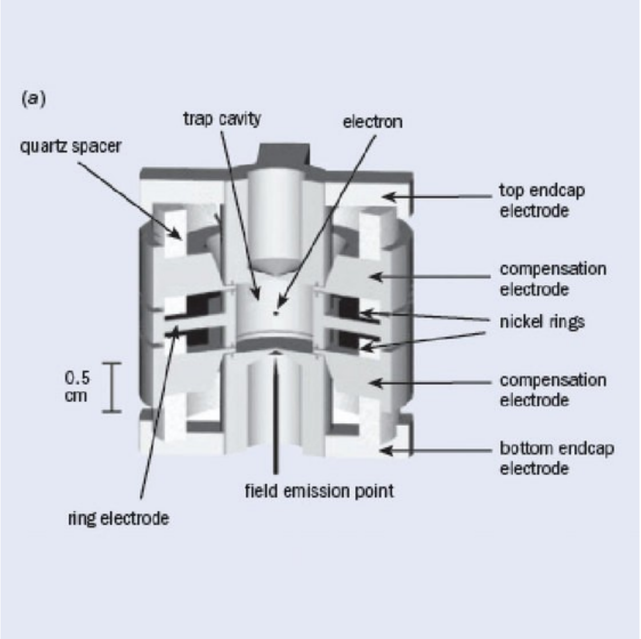
My Verdict: Probably …

Precision electroweak parameters: an update

Fine Structure Constant

$$\frac{\delta\alpha_{\mathrm{em}}}{\alpha_{\mathrm{em}}} \approx 0.32\,\mathrm{ppb}$$

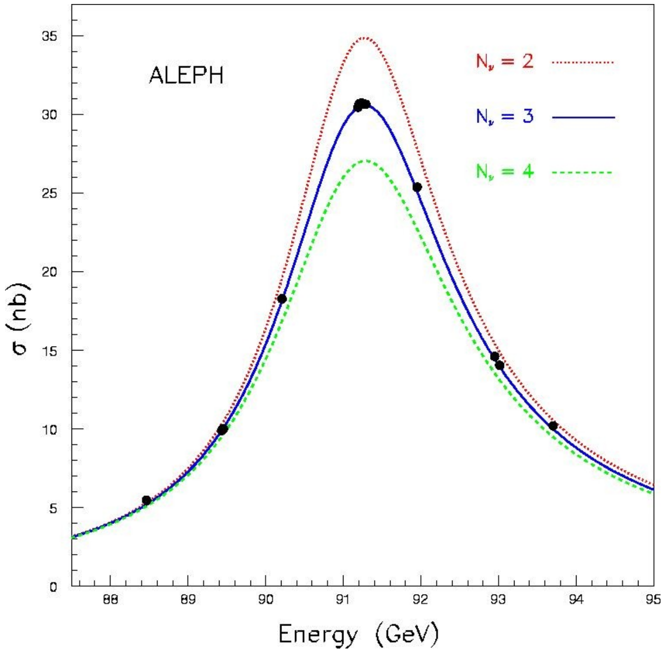
Gabrielse *et al*
2008



Mass of the neutral weak boson

$$\frac{\delta M_{Z^0}}{M_{Z^0}} \approx 23\,\mathrm{ppm}$$

LEP EWWG
2005

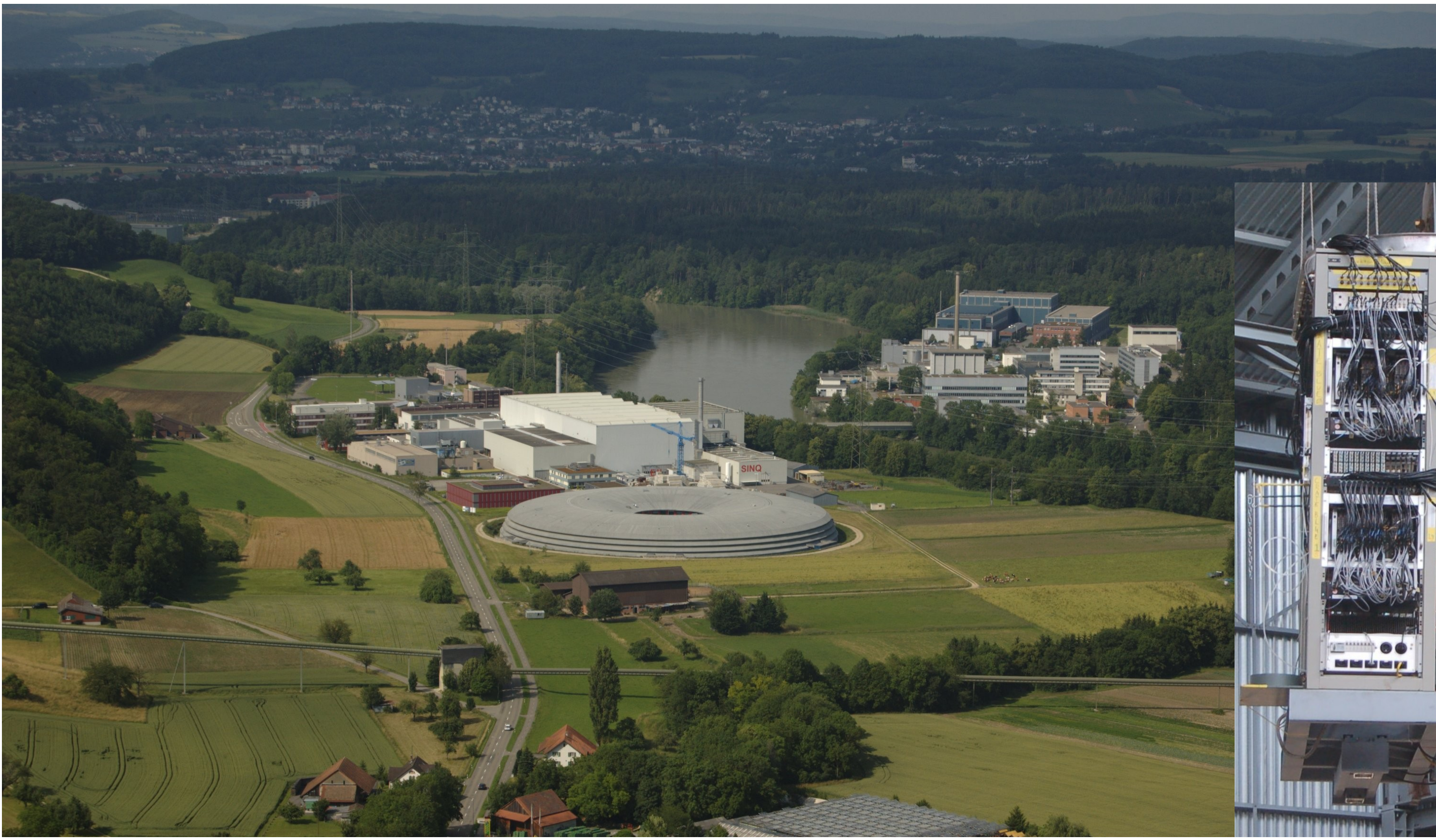


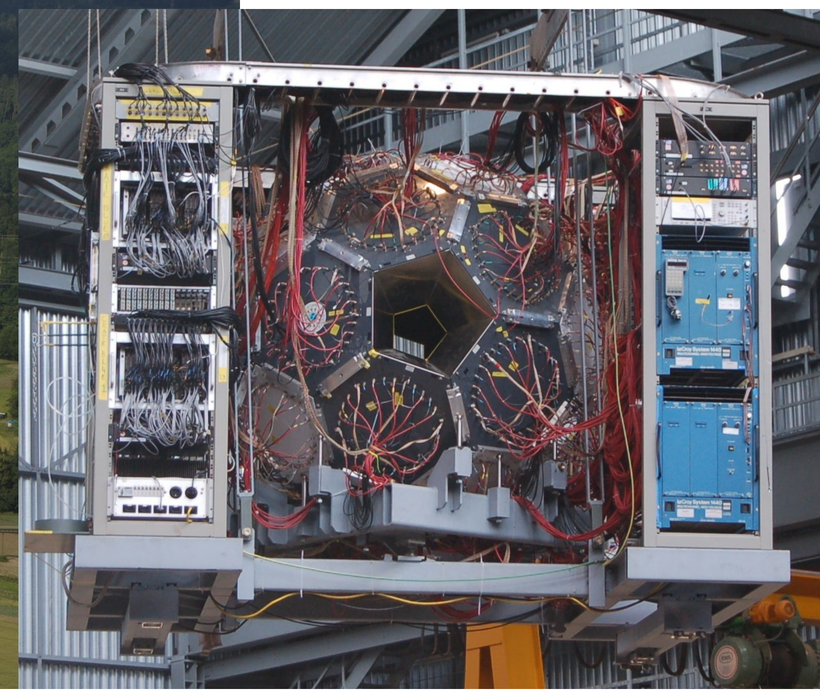
Fermi Constant

$$\frac{\delta G_{\mathrm{F}}}{G_{\mathrm{F}}} \approx 0.5\,\mathrm{ppm}$$

Tishchenko, et al
2012

Special thanks to my Mulan colleagues and to PSI for their long support of our efforts.





V. Tishchenko,[1] S. Battu,[1] R.M. Carey,[2] D.B. Chitwood,[3] J. Crnkovic,[3] P.T. Debevec,[3]
S. Dhamija,[1] W. Earle,[2] A. Gafarov,[2] K. Giovanetti,[4] T.P. Gorringe,[1] F.E. Gray,[5] Z. Hartwig,[2]
D.W. Hertzog,[3,6] B. Johnson,[7] P. Kammel,[3,6] B. Kiburg,[3] S. Kizilgul,[3] J. Kunkle,[3] B. Lauss,[8]
I. Logashenko,[2] K.R. Lynch,[2,9] R. McNabb,[3] J.P. Miller,[2] F. Mulhauser,[3,8] C.J.G. Onderwater,[3,10]
Q. Peng,[2] J. Phillips,[2] S. Rath,[1] B.L. Roberts,[2] D.M. Webber,[3] P. Winter,[3] and B. Wolfe[3]
(MuLan Collaboration)

Residual polarization of the stopped muons plays havoc with lifetime fits

Weak decay
violates chirality

$$\frac{\mathrm{d}\Gamma^{\pm}}{\mathrm{d}(\cos\theta)} = \frac{1}{\tau_\mu}\left(1 \pm \frac{1}{3} A \cos\theta\right)$$

$$N_D(t) = N_0 e^{-t/\tau}\left(1 + \frac{1}{3} A \left[\vec{S}_\perp(t) \cdot \hat{e}_D e^{-t/T_\perp} + \vec{S}_\parallel(0) \cdot \hat{e}_D e^{-t/T_\parallel}\right]\right)$$

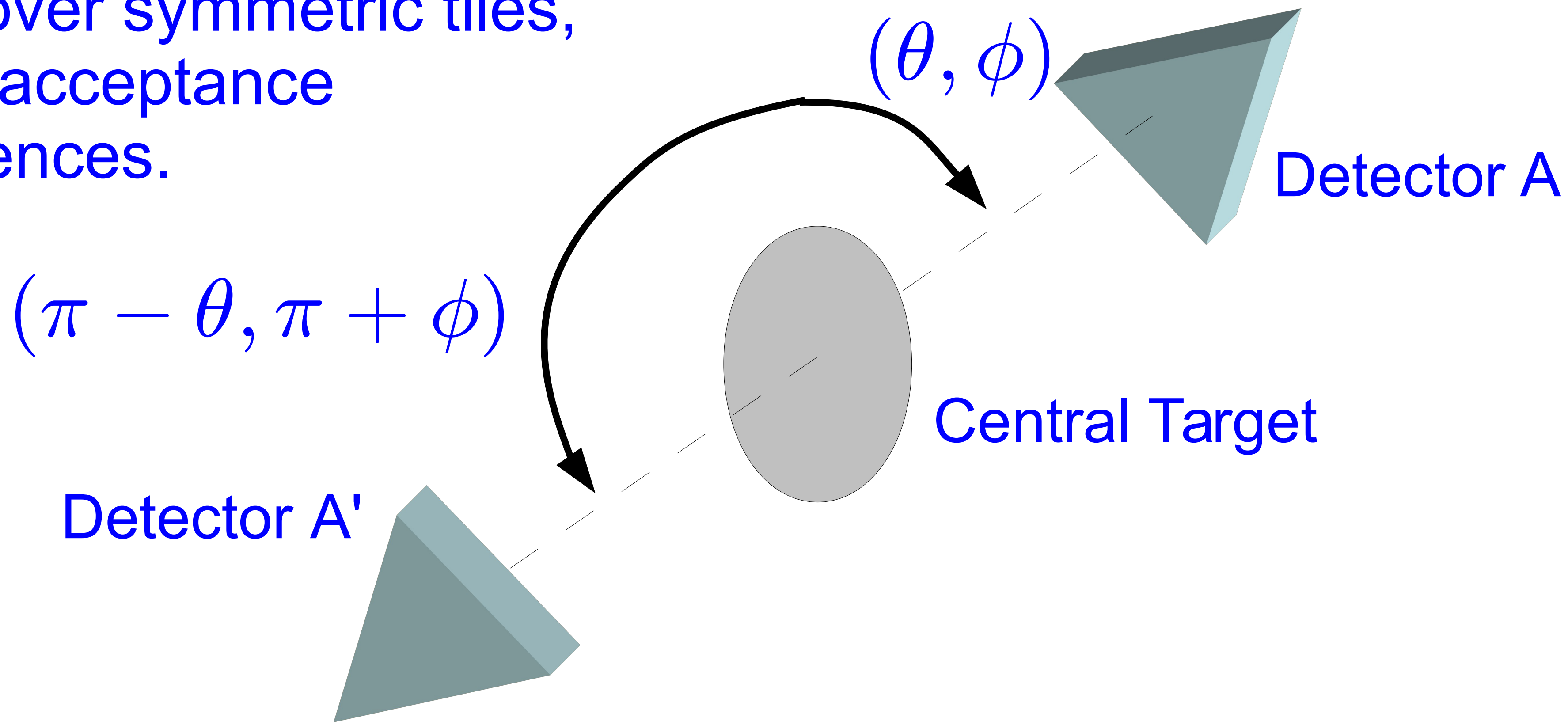
Spins precess in
magnetic fields

$$H = -\vec{\mu} \cdot \vec{B}$$

Matter interactions decrease
polarization fraction over
time

We start with nearly 100% polarized beam ... how do we control polarization issues?

Point symmetry of the detector largely cancels polarization asymmetries in sum over symmetric tiles, up to acceptance differences.



We also modulate the remnant polarization by choice of target environment and muonium formation fraction

A polarization destroying ferromagnetic target, AK3, with high internal field (2004,2006)

Polarization preserving target, crystalline quartz, with an applied external field (2007)

We also performed special runs with polarization maximizing targets like copper and aluminum, and target offsets to maximize asymmetries (2006, 2007)